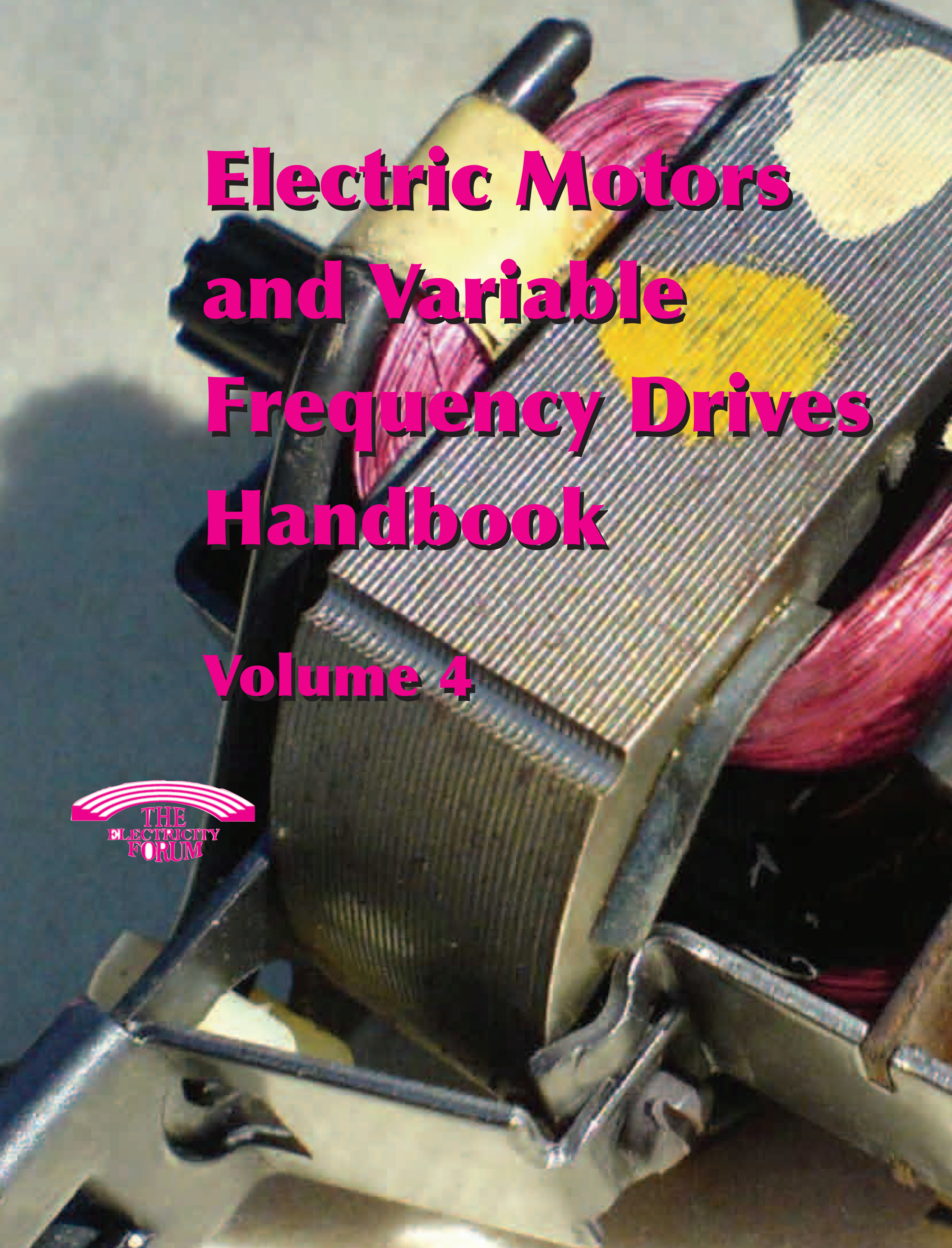

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ELECTRIC MOTORS AND VARIABLE FREQUENCY DRIVES HANDBOOK

VOLUME 4

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VARIABLE FREQUENCY DRIVES

Courtesy: Natural Resources Canada, Office of Energy Efficiency

WHAT IS A VARIABLE FREQUENCY DRIVE?

Adding a variable frequency drive (VFD) to a motor-driven system can offer potential energy savings in a system in which the loads vary with time. VFDs belong to a group of equipment called adjustable speed drives or variable speed drives. (Variable speed drives can be electrical or mechanical, whereas VFDs are electrical.) The operating speed of a motor connected to a VFD is varied by changing the frequency of the motor supply voltage. This allows continuous process speed control.

Motor-driven systems are often designed to handle peak loads that have a safety factor. This often leads to energy inefficiency in systems that operate for extended periods at reduced load. The ability to adjust motor speed enables closer matching of motor output to load and often results in energy savings.

HOW DOES A VFD WORK?

Induction motors, the workhorses of industry, rotate at a fixed speed that is determined by the frequency of the supply voltage. Alternating current applied to the stator windings produces a magnetic field that rotates at synchronous speed. This speed may be calculated by dividing line frequency by the number of magnetic pole pairs in the motor winding. A four-pole motor, for example, has two pole pairs, and therefore the magnetic field will rotate 60 Hz/2 = 30 revolutions per second, or 1800 rpm. The rotor of an induction motor will attempt to follow this rotating magnetic field, and, under load, the rotor speed "slips" slightly behind the rotating field. This small slip speed generates an induced current, and the resulting magnetic field in the rotor produces torque.

Since an induction motor rotates near synchronous speed, the most effective and energy-efficient way to change the motor speed is to change the frequency of the applied voltage. VFDs convert the fixed-frequency supply voltage to a continuously variable frequency, thereby allowing adjustable motor speed.

A VFD converts 60 Hz power, for example, to a new frequency in two stages: the rectifier stage and the inverter stage. The conversion process incorporates three functions:

Rectifier stage: A full-wave, solid-state rectifier converts three-phase 60 Hz power from a standard 208, 460, 575 or higher utility supply to either fixed or adjustable DC voltage. The system may include transformers if higher supply voltages are used.

Inverter stage: Electronic switches – power transistors or thyristors – switch the rectified DC on and off, and produce a current or voltage waveform at the desired new frequency. The amount of distortion depends on the design of the inverter and filter.

Control system: An electronic circuit receives feedback information from the driven motor and adjusts the output voltage or frequency to the selected values. Usually the output voltage is regulated to produce a constant ratio of voltage to frequency (V/Hz). Controllers may incorporate many complex control functions.

Converting DC to variable frequency AC is accomplished using an inverter. Most currently available inverters use pulse width modulation (PWM) because the output current waveform closely approximates a sine wave. Power semiconductors switch DC voltage at high speed, producing a series of short-duration pulses of constant amplitude. Output voltage is varied by changing the width and polarity of the switched pulses. Output frequency is adjusted by changing the switching cycle time. The resulting current in an inductive motor simulates a sine wave of the desired output frequency (see Figure 1). The high-speed switching of a PWM inverter results in less waveform distortion and, therefore, lower harmonic losses.

The availability of low-cost, high-speed switching power transistors has made PWM the dominant inverter type.

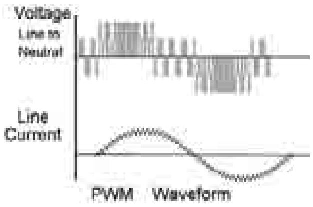


Figure 1. Inverter's Pulse Width Modulation Output

APPLICATIONS

Variable speed drives are used for two main reasons:

- to improve the efficiency of motor-driven equipment by matching speed to changing load requirements; or
- to allow accurate and continuous process control over a wide range of speeds.

Motor-driven centrifugal pumps, fans and blowers offer the most dramatic energy-saving opportunities. Many of these operate for extended periods at reduced load with flow restricted or throttled. In these centrifugal machines, energy consumption is proportional to the cube of the flow rate. Even small reductions in speed and flow can result in significant energy savings. In these applications, significant energy and cost savings can be achieved by reducing the operating speed when the process flow requirements are lower.

In some applications, such as conveyers, machine tools and other production-line equipment, the benefits of accurate speed control are the primary consideration. VFDs can increase productivity, improve product quality and process control, and reduce maintenance and downtime. Decreasing cost and increasing reliability of power semiconductor electronics are reasons that VFDs are increasingly selected over DC motors or other adjustable speed drives for process speed control applications.

Motors and VFDs must be compatible. Consult the manufacturers of both the VFD and the motor to make sure that they will work together effectively. VFDs are frequently used with inverter-duty National Electrical Manufacturers Association (NEMA) design B squirrel cage induction motors. (Design B motors have both locked rotor torque and locked rotor current that are normal.) De-rating may be required for other types of motors. VFDs are not usually recommended for NEMA design D motors because of the potential for high harmonic current losses. (Design D motors are those that have high locked rotor torque and high slip.)

ADDITIONAL BENEFITS OF VFDS

In addition to energy savings and better process control, VFDs can provide other benefits:

- A VFD may be used for control of process temperature, pressure or flow without the use of a separate controller. Suitable sensors and electronics are used to interface the driven equipment with the VFD.
- Maintenance costs can be lower, since lower operating speeds result in longer life for bearings and motors.
- Eliminating the throttling valves and dampers also does away with maintaining these devices and all associated controls.
- A soft starter for the motor is no longer required.
- Controlled ramp-up speed in a liquid system can eliminate water hammer problems.
- The ability of a VFD to limit torque to a user-selected level can protect driven equipment that cannot tolerate excessive torque.

HOW MUCH WILL I SAVE?

The potential energy savings from installing a VFD is illustrated in the following example. Here, a 40 hp motor is used in an HVAC system with a flow-control damper. The system operates 365 days a year with the load/time profile shown in Table 1. The damper is removed and a VFD installed. The estimated annual energy savings realized from the use a VFD is shown in Table 1.

Table 1. Potential Energy Savings From Replacing a Damper With a VFD

Airflow Volume (percent of maximum)	Daily Operating Time (hours)	Energy Consumed Using a Damper (kWh/year)	Energy Consumed Using a VFD (kWh/year)	Difference in Energy Consumption (kWh/year)
50%	2	18 500	4 800	13 700
60%	3	29 300	9 800	19 500
70%	6	61 700	26 800	34 900
80%	6	63 300	35 900	27 400
90%	4	44 200	32 600	11 600
100%	3	34 200	35 200	–1 000
Total	**24**	**251 200**	**145 100**	**106 100**

The above example shows a possible electrical energy saving of 106 100 kWh per year, resulting from replacement of the existing damper-control system with a VFD. Savings would be less if the existing flow-control system used variable inlet vanes. At energy rates of $0.085/kWh, annual savings are $9,018.

At an estimated cost of $4,200 for the VFD and $750 for line and load reactors, the simple payback period is approximately seven months. When installation costs are added, the payback increases to one year.

PURCHASING TIPS

ANALYZE THE SYSTEM AS A WHOLE

Since the process of converting incoming power from one frequency to another will result in some losses, energy savings must always come from optimizing the performance of the complete system. The first step in determining the energy savings potential of a system is to thoroughly analyze the operation of the entire system. Detailed knowledge of the equipment operation and process requirements are required in order to ensure energy savings.

The most promising candidates for realizing energy savings are systems for centrifugal fans, blowers and pumps that have been designed to meet peak loads but actually operate at reduced load for extended periods. The following discussion pertains to centrifugal systems, but the same principles can be applied to other systems. Evaluating the energy-saving potential of a centrifugal system should include the following steps:

1. Develop a complete understanding of the process requirements and the equipment to which the centrifugal machine supplies fluid.
2. Obtain complete engineering specifications and performance curves for the centrifugal machine.
3. Obtain specifications for all components of the system, including dampers, valves, ducts or pipes, and heating or cooling coils.
4. Develop a load/time profile for the system. This step is critical for calculating accurate energy savings. For each component, list annual hours, all flow conditions and the input power to the centrifugal machine.

For each point in the above step, calculate the input power required by a VFD-driven motor and centrifugal machine delivering the same flow. Input shaft power can be determined from the centrifugal machine performance curves.

For each operating point, calculate the difference in power resulting from adding a VFD, and multiply each by the number of hours of annual operation. The difference is the energy savings resulting from installing a VFD.

The above process requires qualified staff with sufficient expertise with all components of the system, from VFD through to the process equipment.

Pump and fan affinity laws govern the relationship among speed, flow and input power. The laws state:

- flow is proportional to speed
- pressure increases with the square of the speed
- power increases with the cube of the speed

When speed is reduced to 75 percent of design speed, flow decreases to 75 percent, outlet pressure decreases to 56 percent, and the input power requirement drops to 42 percent of full-speed values. For a similar flow reduction with a throttling valve or damper, the input power drops to only 80 percent. Note that pressure falls off more rapidly than flow.

VFD AND MOTOR SELECTION

Once you have verified the energy savings achievable using a VFD in your application, the following topics should be considered when selecting a motor and drive combination.

IS SOFTWARE AVAILABLE TO HELP CHOOSE A VFD AND ESTIMATE SAVINGS?

Most VFD manufacturers can provide such software.

Free software is also available. ABB offers Energy Saving Tools: PumpSave for comparing AC drive control against throttling, on/off and hydraulic coupling control in pumps; and FanSave, for comparing AC drive control with traditional flow-control methods in fans.

WILL THE MOTOR WITHSTAND THE REPETITIVE VOLTAGE STRESSES FROM USE OF A VFD?

General-purpose induction motors are not designed for repetitive voltage overshoots that exceed line voltage plus 1000 volts. With a 230 VAC system, overshoots may not exceed this limit, but with a 575 VAC system, overshoots are likely. Repeated voltage stresses may lead to insulation breakdown and premature motor failure.

To use a VFD with an existing general-purpose motor, additional filtering and transient protection may be required. NEMA definite-purpose motors rated “Inverter Duty” are recommended for use with VFDs. These motors can withstand repetitive voltage spikes that are 3.1 times the rated RMS voltage.

WHAT NEMA DESIGN TYPE IS BEST SUITED FOR A VFD?

VFD control algorithms are usually optimized to the speed torque characteristics of NEMA design B motors. Use of other design types should be discussed with the VFD manufacturer.

SHOULD I USE A MOTOR THAT HAS A DIFFERENT POLE COUNT (I.E., SIX-POLE INSTEAD OF FOUR-POLE)?

A VFD may be able to provide the required speeds with better performance using a motor that has a different number of poles. This can reduce the inventory of spares. The use of a bypass, however, may limit the number of choices of pole count. Be sure to discuss your options with the VFD manufacturer.

IS MOTOR COOLING ADEQUATE FOR EXTENDED OPERATION AT VERY LOW SPEEDS?

Cooling often depends on motor speed, such as with totally enclosed fan-cooled (TEFC) motors. To meet constant torque loads, therefore, a motor should not be operated at less than 30 percent speed without additional cooling. Consider a larger motor, constant speed cooling or a totally enclosed non-ventilated (TENV) motor for these conditions. Motor thermal protection devices will prevent high-temperature damage when motors operate continuously at very low speeds. With variable torque loads such as centrifugal machines, the rapidly decreasing power at low speed reduces cooling problems.

WILL HARMONICS AFFECT NEARBY SENSITIVE EQUIPMENT?

Additional line filtering is often required to reduce the propagation of harmonics and radio frequency interference (RFI) to other equipment. Short leads between the motor and the VFD help minimize RFI propagation. When leads are longer than 15 metres (50 feet), reactive filters are recommended. Motor leads should also be enclosed in a rigid conduit to reduce RFI.

IS THE VFD STARTING TORQUE AND ACCELERATION/DECELERATION ADEQUATE FOR THE LOAD?

The VFD breakaway torque is less than the motor locked rotor torque and is limited by the VFD maximum current rating. This current rating also limits the rate of load acceleration. Acceleration, deceleration and maximum current are user-programmable.

CAN A VFD BE USED FOR ALL TYPES OF LOADS?

Yes. VFDs for use with constant torque loads should be rated for operation at 150 percent load for a period of one minute. Variable torque loads such as fans and pumps are easier to start, and therefore the VFD overload rating is lower. The drive should be matched to the load.

DOES THE APPLICATION HAVE A HIGH STATIC PRESSURE OR HEAD?

Applications in which a minimum pressure must be maintained may not be suitable candidates for a VFD. For example, if high pressure is required even at low flow, it may not be possible to significantly reduce pump speed. When speed and flow reduce, so does pressure. For this application, other energy-saving strategies such as parallel pumps may offer more energy savings. Check the pressure limitations in your system. More information on VFD pumping applications is in Variable Speed Pumping – A Guide to Successful Applications, available from the U.S. Department of Energy’s Industrial Technology Program.

WHAT TYPE OF ENCLOSURE IS REQUIRED?

Check the ratings of both the drive and its enclosure to make sure that they are suitable for the climate to which they will be exposed (i.e., outdoor weather protection).

IS SPEED CONTROL ACCURACY IMPORTANT FOR MY APPLICATION?

Most VFDs incorporate a user-programmable, constant volts-to-frequency ratio over the operating frequency range of the drive. For more accurate speed control, a flux vector control strategy with either direct or indirect measurement of rotor flux may be required.

IS DIRECTION OF ROTATION AFFECTED?

The phase sequence of the supply connection to the VFD does not affect the rotation direction of the drive. Changing the phase sequence between the drive and the motor will change the direction of rotation of the motor. Be sure to verify rotation before connecting the drive to the equipment. Some equipment may be damaged if rotation is reversed. If a bypass contactor is used with a VFD, be sure that the rotation direction is correct during bypass operation

DOES THE APPLICATION REQUIRE DYNAMIC BRAKING?

Load braking is usually accomplished by switching in a power load resistor across the DC bus to dump excess energy. This is usually an optional feature that is available only with some drives.

HOW MANY MOTORS CAN BE OPERATED ON A DRIVE?

More than one motor on a drive is common. All receive the same frequency, so they change speed in unison. Each motor must have its own overload protection.

DO I REQUIRE REMOTE MONITORING OR FLEXIBLE CONTROL AND SET-UP SOFTWARE?

You may need drive monitoring and set-up software with RS-485 multi-drop communication. RS-485 allows monitoring and control of several drives from a remote location.

DO I NEED BYPASS SWITCHING?

Bypass switches are sometimes used so that a motor can operate when connected directly to the utility power supply. This enables operation of the motor when the drive is out of service.

ELECTRIC MACHINES

ROBERT K. ADYKOWSKI

HISTORY

Electric machines have experienced a wide acceptance since 1997 and now are positioned to be the new standard of the molding industry. For the year 2000, these machines represented 20% of the new machines less than 500 tons being ordered in North America.

The electrification of the molding machine follows other similar evolutions in industry to increase accuracy and provide more predictable processing capabilities. The machine tool and robot areas have seen this same evolution from hydraulic actuation to AC servo drives since 1965.

MAJOR DESIGN CONSIDERATIONS

The major design considerations in the development of the electric machines were to:

1. provide to the user a machine with better capability of process control
2. eliminate the variances of a hydraulic system
3. provide a reduction of energy used in the conversion of plastic materials

Using basic motion control from the machine tool industry for the linear and rotary motions required in an injection molding machine provided the basis for the machine actuation.

Toggle-clamp technology of an injection molding machine was used as the basis for the clamp unit along with an AC servo motor drive and a ball screw. Ejector motion was also replicated by using an individual AC servo motor drive/ball screw combination. Injection functions were replicated by using individual AC servo motor drives for the plasticizing function and linear injection function. Pressure control was first investigated using torque control of the injection motor, but this was dropped for the advantage of a strain gauge control and direct plastic pressure readings.

Substituting direct mechanical motion that eliminated the hydraulic oil completely eliminated hydraulic system variation. The elimination of the hydraulic system decreased reaction time of the various control/motion functions, providing quicker response to control signals. The lack of the hydraulic system also eliminated the need for a cooling system for the oil a major source of variation in the process.

Energy utilized in the overall injection process is in large part attributable to the hydraulic pump and the need to have oil under pressure ready for the various functions of the machine. If one considers that the pump runs 100% of the operational time, but that actual oil movement is only approximately 40% of the time, the hydraulic system wastes up to 60% of the energy it consumes. An electric machine utilizes only the energy necessary at the time movement is required, therefore eliminating the majority of the conversion cost. Heat generated b the hydraulic system is also eliminated along with the need for a heat exchanger to remove the heat.

SERVO DRIVE DEVELOPMENT

AC servo-driven electric injection molding machines were introduced as a commercial product at the 1985 NPE. Electric motors have been used on various axes (e.g., extruder drive) of machines since the late 1950s. The first electric drive was used for screw rotation through a selectable gear-driven speed control with the option of various gear ratios. This electric drive of the extruder function introduced in the early 1960s on NATCO machines is still a popular energy saving method in machines today.

AC servo drives were first developed in 1974 by FANUC through the vision of Dr. Seiuemon Inaba (1), resulting from the oil shortage and increased power costs. He had previously developed a hydraulic servomotor but knew its limitation. His perfection of the AC servo motor revolutionized the machine tool industry and later dominated the robot industry. AC servo motors are the standard in these industries today. Linear motion is achieved by coupling the rotary motion of the AC servomotors to ball or roller screws to provide the same action as a hydraulic cylinder.

Ball screws have been utilized in machine tool equipment since the early 1950s providing a zero backlash device to translate rotary motion into linear motion with minimal energy loss. These drive devices are also used in multiaxis robotics, providing repeatability of positions with each movement.

ENERGY SAVINGS

The advantages of electric actuation start to show with this combination because the mechanical transfer of energy through this method is better than 95% efficient. This represents a large energy savings because the motors only operate when required rather than maintaining full loading, as in the case of a hydraulic pump. Total energy savings versus a newer hydraulically operated toggle machine is in the 65-75% range, depending on cycle times (Figure 1).

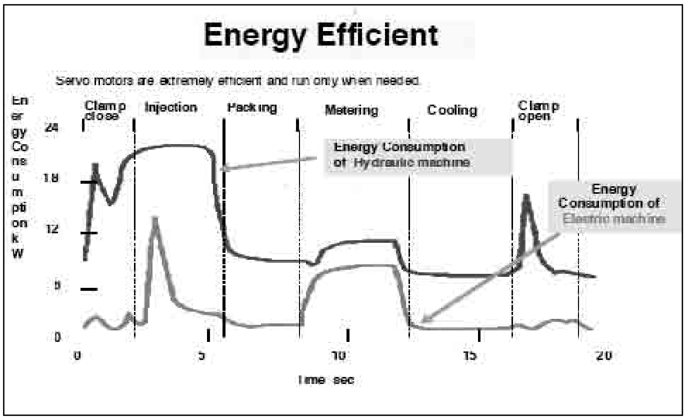


Figure 1. energy savings versus newer hydraulically operated toggle machine.

Cycle times of 30 seconds or more can easily represent savings as high as 80-90%. In addition, no power spikes as seen in standard motors exist with AC servo motors. No power factor correction is required because of the operational characteristics of an AC servo motor.

When rapid cycle times are required (5 seconds and lower) and independent and simultaneous motions are required of a machine, the electric machines save even higher percentages of electric energy. They also represent a much lower investment cost because this type of operation requires only software changes, rather than expensive second independent hydraulic systems.

HYDRAULIC/ELECTRIC DIFFERENCES

The application of AC servo technology and ball screws, along with time proven toggle clamp mechanisms, has provided machines up to 1500 tons of clamp capacity. These machines have been limited in some cases because of the servo motor size in the area of injection capacity. Designs of two-stage injection units have eliminated this issue, and the large machine is now poised to take its place in the industry (Figure 2).

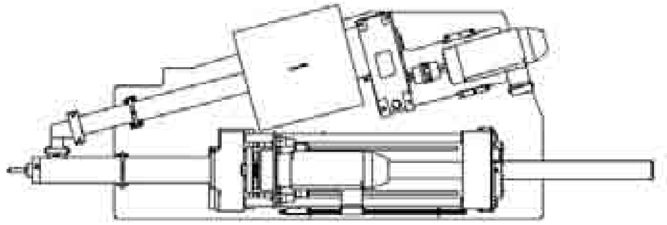


Figure 2. Two-stage injection unit machines

The difference between a hydraulically actuated machine and an electrically actuated machine is that a single motor/pump drives all motion of the hydraulic machine. Electric AC servo-driven machines utilize an independent drive motor for each linear or rotational movement of the machine. The typical electric machine today includes individual AC servo motor drives for the clamp axis; eject axis, extruder rotation axis, and linear travel of the injection screw. In addition, there are usually two additional motor drives, one for die height adjustment and a second for injection sled movement (Figure 3).

Each of the drives is independently actuated, as required, providing a machine capable of running all axes movement at the same time. This is not commonly done; however, simultaneous movement of the clamp and ejectors is commonplace. In addition simultaneous rotation of the screw and linear movement of the screw during clamp movement is only a software change rather than the addition of separate or larger hydraulic pumps.

One of the unique thought patterns that change when using an electric machine is that the technician changes from doing anticipatory settings to setting actual requirements. The control of the machines precludes the press from doing anything other than what is programmed into the control. It performs at the set speeds and stops at the exact positions. Unlike a hydraulic machine, the speed and pressure functions are no longer coupled – rather, they are independent of each other. This allows for a much wider processing window and set up capability.

Electric machines provide a whole new capability to the technician and operation people in today's modern molding plant because they provide both speed and position control beyond that of hydraulic-driven machines. It is not uncommon to have position control of ± 0.004 in. from set point. These close tolerances are achievable regardless of the velocity. Rotary optical encoders sense position and speed of each individual servo motor to closer tolerances than the typical LVDT used to monitor hydraulic cylinder strokes.

This accuracy becomes very useful when applying automation to insert loading or part removal because the clamp or ejectors are always in the exact position. It is also useful when operating molds with sliding cores because slowdown does not need to occur until just before engagement of the slide actuator. Because of the accuracy of the machines it is necessary to double check that all ejector bars are within 0.004 in. in length; otherwise, side loading occurs and can damage molds and machines.

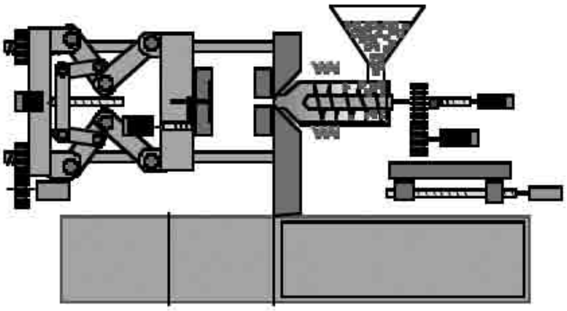


Figure 3. Electric machine with two additional motor drives

DRIVE BASIC SYSTEMS AND COMPONENTS

Courtesy of GE Industrial Control Systems

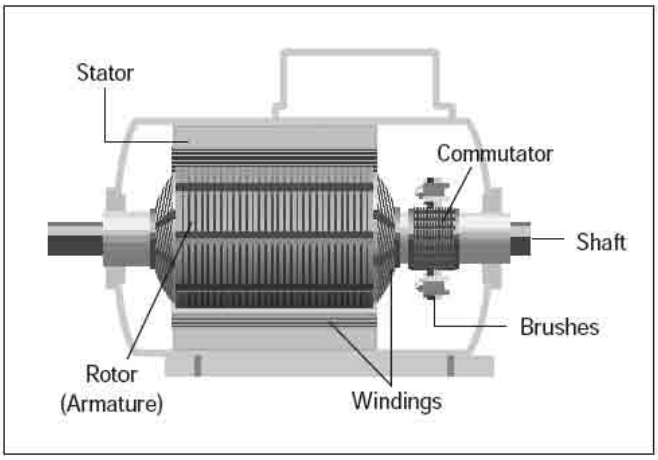
There are two main types of motors: DC and AC. DC motors operate on DC power, while AC motors operate on AC power. All motors have two basic components – a stationary part, called the stator, and a rotational part, called the rotor. In DC motors, the rotor is more commonly referred to as the armature.

The rotor/armature sits inside of the stator. Electricity (current) flowing through the motor creates a magnetic field, which attracts (or repels) the rotor, causing it to spin. The shaft is the part of the rotor that extends outside of the motor and connects to the equipment to be rotated.

DC MOTORS

DC motors are based on a stationary magnetic field. The stator of a DC motor consists of windings that are made of coiled wire to form a magnetic pole. When current flows through the windings, they produce a magnetic field. The poles are connected to the inside of the frame (or shell) of the motor. The armature also has windings that create a magnetic field when voltage is applied (in most DC motors, the armature and stator receive electricity from separate sources).

There are a series of windings running lengthwise down the armature. Voltage is applied to one set of windings in the armature at a time. When this occurs, the windings become magnetic and are attracted to the magnetic field in the stator. The armature spins to align itself with the stator. When the rotor moves, another set of windings in the armature becomes connected to the power supply. The windings become magnetic and attracted to the stator field, and the rotor moves again to align itself with the stator. This process keeps the rotor spinning within the stationary magnetic field in the stator.



AC MOTORS

AC motors utilize a rotating magnetic field within the stator. The stator of an AC motor is also made up of windings. There is a set of windings for each phase of AC power, distributed around the stator. A set of three windings (one from each phase) forms the magnetic pole. When AC voltage is applied, one set of windings is activated by one phase and creates a magnetic field. The next set of windings becomes magnetic when the next phase of power is fully active. The rotor of an AC motor is made out of metallic bars. The bars feel the pull of the magnetic field in the active windings, spinning the rotor as they align. When the next set of windings is excited by the next phase, the rotor spins again. AC electricity creates a rotating magnetic field in the stator, to which the rotor continually tries to align itself. The speed at which the AC motor rotor rotates depends on how many poles are in the stator and the frequency of applied power. The more poles there are, the slower the rotor will spin. The higher the frequency of power, the faster the motor will spin.

TORQUE AND HORSEPOWER

The motor torque refers to how much force the motor shaft exerts as it rotates. Torque is dependent on the strength of the magnetic fields in the motor – a stronger magnetic field will exert a stronger pull on the rotor, creating more torque. The force of the magnetic field, and thus torque, is determined by the amount of voltage and frequency supplied to the motor. The horsepower of a motor refers to how much work the motor can do, or how much torque it can deliver over time. The relationship between torque and horsepower is:

$$\text{HORSEPOWER (HP)} = \frac{\text{TORQUE (FT-LB)} \times \text{SPEED (RPM)}}{5252}$$

The speed at which the AC motor rotor rotates depends on how many poles are in the stator and the frequency of applied power.

Torque is dependent on the strength of the magnetic fields in the motor – a stronger magnetic field will exert a stronger pull on the rotor, creating more torque.

LOADS

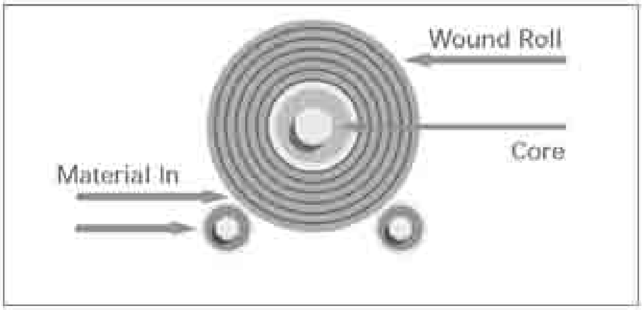
The nature of the load dictates what type of motor is needed and how it needs to be controlled.

The load dictates what type of motor is needed and how the motor needs to be controlled. Some load characteristics that need to be considered are speed, torque, weight, tension, and inertia. Whether or not these characteristics are constant or vary over time also needs to be considered.

Motors are used to rotate other mechanical machines. The equipment being driven by the motor is called a load. The load dictates what type of motor is needed and how the motor needs to be controlled. Some load characteristics that need to be considered are speed, torque, weight, tension, and inertia. Whether or not these characteristics are constant or vary over time also needs to be considered. In a simple load, only one of these characteristics affects the load at one time. In a complex load, multiple characteristics may change over time. Load characteristics also determine whether or not the load can be classified as constant horsepower, constant torque, or variable torque.

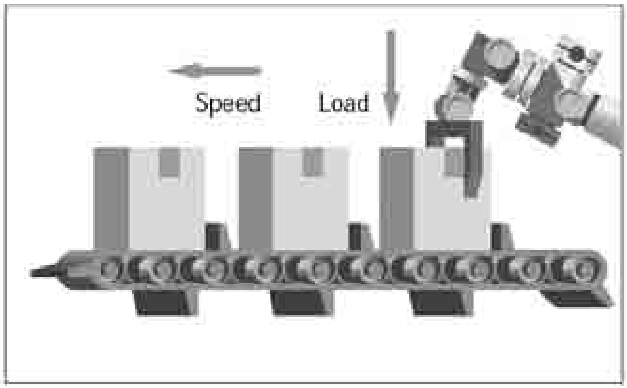
Constant horsepower loads are those in applications where the amount of work to be done is independent of speed and torque. Loads that require constant tension require constant horsepower. An example of a constant horsepower application is a winder. A winder is a roller onto which processed material, such as paper, is wound. As the process of making paper continues, more and more paper is wound around the winder. The diameter of the roll increases, as does the weight of the load. As the diameter of the roll increases, the speed of the winder must slow down to maintain constant tension (otherwise the paper would tear or sag). However, the amount of work that needs to be done doesn't change.

Other applications involving constant horsepower loads are: Drills, grinders, lathes, milling machines, wire drawing machines, and cutting machines.



Constant torque loads are the most common in industrial applications. The amount of force needed is independent of speed. An example of a constant torque application is a conveyor belt.

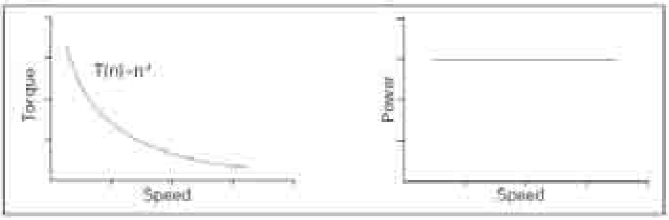
No matter how fast the conveyor belt is going, or how much is loaded onto it, the conveyor must exhibit the same force so that the conveyor runs smoothly without throwing off the load.



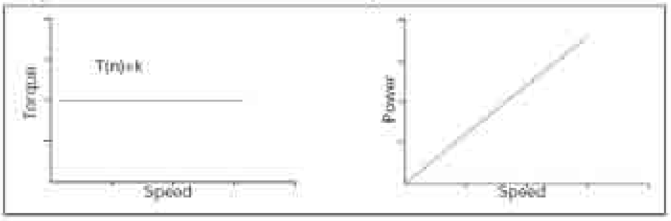
Other applications with a constant torque load include: Coaters, cranes, elevators, forming mills, galvanizing lines, planers, and textile spinners. Typically, drives that are built to handle constant torque loads are capable of handling up to 150% of rated current for 60 seconds. Rated current is the amount of current flowing through the drive/motor when under full load.

Variable torque loads exhibit both an increase in torque and horsepower as speed increases. An example of a variable torque load is a fan. The load includes the fan blades, as well as the centrifugal force felt by the fan. As the fan spins faster, there is more air resistance and centrifugal force to deal with. Pumps are another example of variable torque loads.

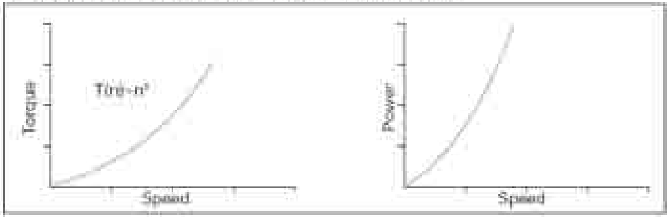
Torque Characteristics of Constant Horsepower Loads



Torque Characteristics of Constant Torque Loads



Torque Characteristics of Variable Torque Loads



Note that the two curves for each type of load reflect the relationship between speed, torque, and horsepower.

DRIVE BASICS

A drive may be used to increase the efficiency of a process, provide accurate motor speed, control motor torque, and enable the motor to run at a range of speeds, or to automate and optimize a process.

Drives built to handle variable torque loads can generally handle 110-120% of rated current for 60 seconds. If the nature of the load is not obvious, it must be determined by a field test. The nature of the load dictates what type of motor is needed and how it needs to be controlled.

Drives enhance the performance of motors. In the case of DC motors, a drive is one alternative to creating and controlling a supply of DC electricity. In the case of AC motors, drives allow for a more controlled form of AC power to be supplied.

In either case, a drive may be used to increase the efficiency of a process, provide accurate motor speed, control motor torque, and enable the motor to run at a range of speeds, or to automate and optimize a process. All of these features work to improve the quality of a process run by motors.

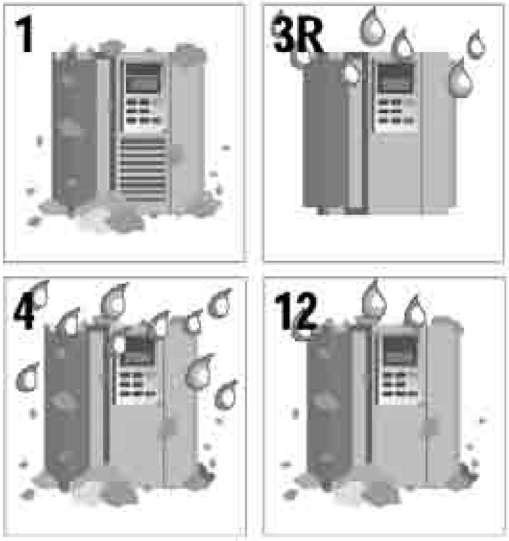
The control aspects of the drive are made up of electrical devices, which are protected by an outer covering, or enclosure. The degree of protection provided by the enclosure is dictated by the drive's operating environment. There are several Standards Associations that define different enclosure types that are suitable for different environments. NEMA (National Electrical Manufacturers Association) creates standards that are primarily followed in the USA, while the IEC (International Electro-technical Commission) writes international standards.

NEMA has defined four enclosure types that are the most widely used on drives.

Type 1 is an enclosure offering protection for indoor locations and must provide protection against limited amounts of falling dirt, but does not need to prevent the entry of dust or liquids into the drive. NEMA Type 3R enclosures are intended for use in the outdoors, and offer protection against falling rain and external ice formation.

A Type 4 enclosure is intended for indoor or outdoor use, and provides protection against falling rain, external ice formation, and windblown rain and dust. Type 12 enclosures are intended for indoor use and provide protection against dirt, dust, nonflammable fibers, splashes, drips (of non- corrosive liquids), and seepage.

The enclosure protects the electrical components that comprise the drive. The internal parts of a drive include electrical devices such as capacitors, rectifiers, resistors, processor chips, and relays. These devices work together to change and control current and voltage.



NEMA Classifications

DC DRIVES

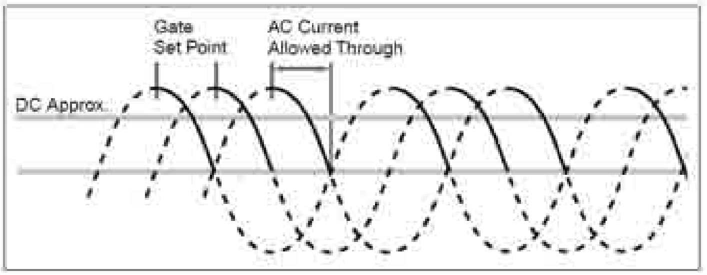
DC drives can control motor speed in two ways – by controlling the voltage supplied to the armature to obtain speeds below the base speed of the motor, or by reducing the current supplied to the field to obtain speeds above the motor's base speed.

DC drives have two main components: A converter and a regulator. A converter is an electrical circuit that converts AC power to DC power. DC drive converters typically use a device called a silicon control rectifier (SCR) for this conversion process. SCRs transform AC current into a tightly controlled form of DC current.

An SCR is a gated transistor that only allows current to pass through it when the current reaches a certain value (the point at which the gate is set), which turns on the SCR. SCRs are only "on" when power is applied to its gate. When SCRs are on, they have the effect of chopping the sine wave of an AC power supply into fragments that approximate a DC power supply.

A regulator is the control portion of the drive. The regulator is the "smarts" or processing logic that determines what voltage and current is supplied to the motor. The voltage output from the drive can manipulate the speed or the torque of the motor (thus, the tension of a process load can also be controlled). The changes to the power supplied to the motor depend on the logic in the regulator and the type of feedback from the motor. Feedback devices, such as encoders or load cells, are sensors on the motor or on a process line that monitor actual process performance. An example of a feedback device is a tachometer (tach), a device that monitors the actual speed of the motor. A tach can send a signal back to the drive telling it how fast the motor is actually running. The drive regulator can compare that signal to a set number programmed into the drive, and determine if more or less voltage is needed at the motor to get the actual speed of the motor equal to the programmed speed. Because DC drives manipulate the voltage supplied to the motor, they are deemed variable voltage control. A drive using feedback sensors is said to have closed loop control.

DC drives can control motor speed in two ways by controlling the voltage supplied to the armature to obtain speeds below the base speed of the motor, or by reducing the current supplied to the field to obtain speeds above the motor's base speed.



Sine Wave and DC Approximation

AC DRIVES

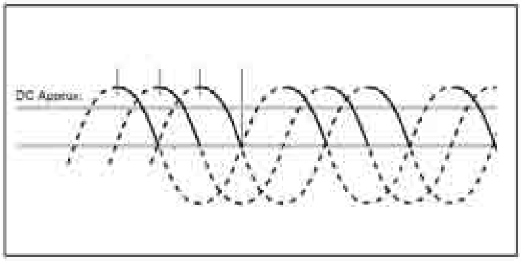
AC drives have three main components: A converter, a regulator, and an inverter. The converter in an AC drive is similar to that in the DC drive – it is used to convert AC power into DC power.

While some AC drives use an SCR, most use a diode rectifier rather than an SCR. Diodes are similar to SCRs, but they do not have a gate and thus cannot be turned on or off. Hence, diode rectifiers are less expensive, but do not provide as tight of voltage control as an SCR.

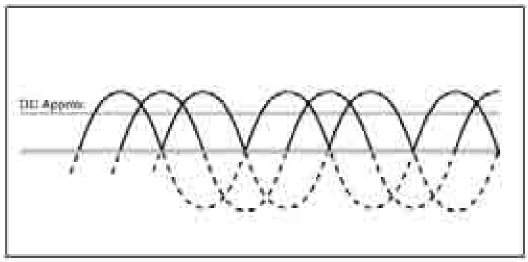
Diodes only allow the positive portion of AC power to be transmitted through the circuit. In an AC drive, the DC power will be converted back into a form of AC power, so the DC approximation does not need to be as accurate. Also, the level of DC voltage does not need to be controlled to control the motor speed.

AC drives also have regulators, which control the DC power before it is further transmitted. AC motors may have their speed and torque controlled as well, depending on the type of regulator.

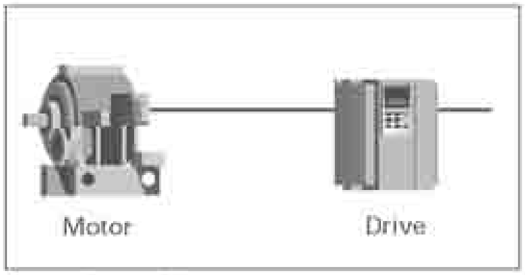
There are three main types of AC regulators. A volts per hertz regulator controls the ratio of voltage to frequency of AC power output to the motor. The speed of an AC motor depends on the frequency; thus the speed is controlled. A volts per hertz regulator does not use feedback devices. An open loop vector regulator also controls motor speed without feedback devices. However, it regulates the current output to the motor, and controls the rotor/shaft speed by controlling the frequency of the magnetic flux in the stator. This type of regulator may also be used to control the torque of a motor.



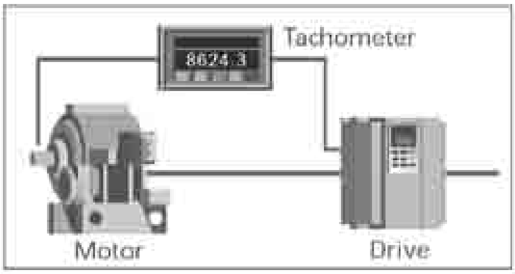
SRC



Diode Rectifier

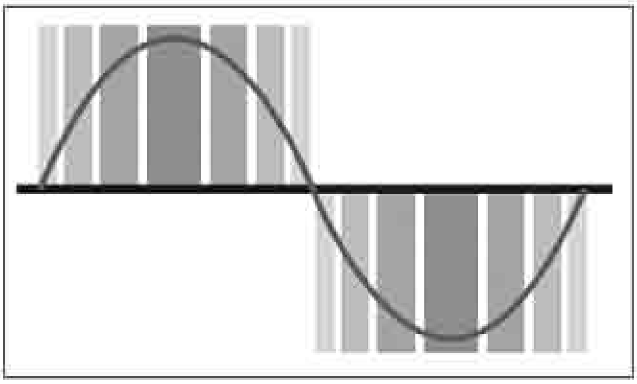


Open Loop Vector



Closed Loop Vector

A closed loop vector regulator (also called flux vector) is similar to an open loop vector drive, but differs in that it uses feedback devices. The third component of an AC drive, the inverter, takes the regulated DC power and changes it back into a form of regulated (controlled) AC power. AC drives typically utilize an Insulated Gate Bipolar Transistor (IGBT) to invert power through a control strategy called Pulse Width Modulation (PWM). IGBTs are capable of turning on and off very fast, allowing pulses of DC voltage to pass through to the motor. These pulses approximate an AC power supply.



PWM Power Approximating AC Power

BRAKING

Drives not only vary the speed at which motors operate, they also offer a means of braking a motor. If a motor is not connected to a drive or equipped with a mechanical brake, it will coast to a stop when the motor is shut off. Braking provides for a controlled form of stopping, whether it is coasting, gradual braking, or quickly halting the motor.

There are two means of braking with the use of drives: Injection braking and Dynamic braking.

Injection braking is only applicable with AC drives and motors. To stop the motor, the drive sends DC current to the motor. Without the varying voltage and frequency in various phases, the magnetic field in the stator stops rotating. The rotor is attracted to the halted field and stops.

Dynamic braking is used when the motor acts as a generator. Changes in the load may cause the motor to act as a generator rather than a motor. An example would be a conveyor belt that is sloped downward – as the weight is added to the belt, the load may pull the motor faster than it would normally operate. In dynamic braking, contactors, or other switching devices, create a circuit in the drive that directs power flow from the motor to resistors. Resistors dissipate power by converting it to heat. This form of controlling power flow slows down or stops the motor.

Regenerative braking is a form of dynamic braking in which the power is dissipated back into the main AC line, rather than through resistors.

This eliminates the wasting of power and also reduces the amount of heat created in the resistors.

BYPASSING

Injection braking is only applicable with AC drives and motors. To stop the motor, the drive sends DC current to the motor.

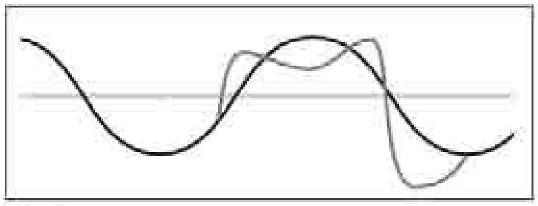
Dynamic braking is used when the motor acts as a generator.

Bypassing the drive means that control of the motor is switched from the drive to a starter.

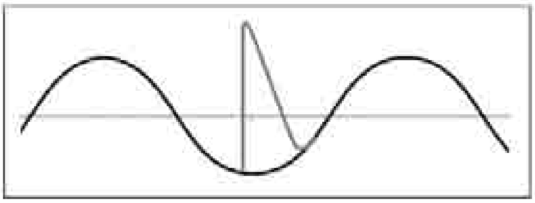
LINE CONSIDERATIONS

Both AC and DC drives create electrical noise that can affect the reliability and performance of the drive, motor, and AC power supply. The magnetic and electrical forces created within the drive cables can induce forces on other electrical devices in close proximity. The resulting disruptions in the power supply are referred to as noise. Noise disrupts the power in nearby cables, which can cause overheating, reduced power factors, circuit breakers to trip, and malfunctions of other devices operating on the power supply. Voltage spikes are a type of noise caused by power surges when drives start up and shut off. Large quantities of voltage can suddenly be transmitted across the line when drives are used.

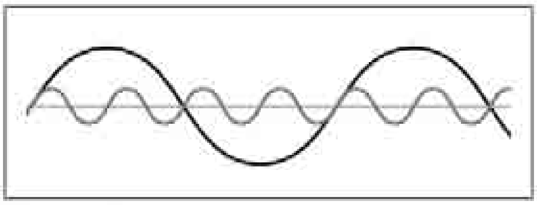
Harmonics are a special type of noise resulting from AC drives. Harmonics are sinusoidal waves with higher frequencies than the main power supply, and are transmitted back to the AC line.



Noise



Voltage Spikes



Harmonics

Drives may be built with special devices to reduce the amount of noise and harmonics created or transmitted. Devices that filter out noise are: Reactors, transformers, harmonic filters, isolation transformers, and 12 or 18 pulse drives.

Drives can be classified as 6, 12, or 18 pulses. The number of pulses is a reference to the number of conduction sequences available in the converter. Twelve and 18 pulse drives produce fewer harmonics than a 6 pulse drive, and the harmonics are at higher frequencies. IEEE (Institute of Electrical and Electronic Engineers) is another association that writes standards.

IEEE 519 is a standard that defines acceptable levels of harmonics.

USER/OPERATOR INTERFACES

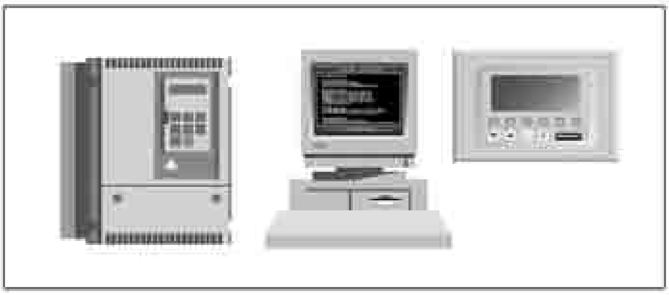
A DRIVE'S USER INTERFACE

Operator interface allows an operator to program control references to the drive/motor system, and to monitor motor and drive operating conditions.

Drives provide a means for developing a control logic based on the status of other devices.

Drives offer a means of controlling a motor. A drive's user interface allows an operator to program control references to the drive/motor system, and to monitor motor and drive operating conditions. Interfaces include start/stop pushbuttons, keypads situated directly on the drive or in a remote location, PCs with drive compatible software, and programmable logic controllers (PLCs). PCs and PLCs are useful when multiple drive systems will be used at one time. They allow for multiple drives to be programmed quickly with the same control references, and also reduce the amount of wiring needed to link the systems together.

They operate on a communications link or industrial network, which allows for high speed and quality process control.



Operator Interfaces

I/O

In most applications, drives are used to control motors in conjunction with other electrical equipment. For example, one motor may be used with a series of other motors in a continual process – the speed of one motor might be dependent upon another motor. If a sensor goes off, the motor might need to stop or slow down.

Drives provide a means for developing a control logic based on the status of other devices.

Drives also display the status of the motor and drive parameters, such as current and speed.

These functions require input and output (I/O) connections within a drive.

There are two types of I/Os: Digital and Analog. Digital I/Os can be either on or off. Examples of digital I/Os would be a start button, fault signal, light, or photosensor. Analog I/Os may have a value within a set range. Examples of analog I/Os would be current level or current operating speed.

GLOSSARY

AC (Alternating Current): A type of current in which the flow of electrons alternates back and forth as the voltage force alternates between pushing and pulling on electrons.

Analog I/O: A type of I/O which may have a value within a set range.

Armature: Another name for the rotor, and which is more commonly referred to in DC motors.

Bypassing: A means of switching control of the motor from the drive to a starter.

Closed Loop Vector: Also called flux vector, this regulator is similar to Regulator an open loop vector drive, but differs in that it uses feedback devices.

Constant Horsepower: Loads in applications where the amount of work to. Load be done is independent of speed and torque, or that require constant tension.

Constant Torque: Load Loads in applications where the amount of force needed is independent of speed, and are the most common in industrial applications.

Converter: An electrical circuit that changes AC power to DC power.

Current: The actual flow, and strength of flow, of electrons.

DC (Direct Current): A type of current in which electrons flow in one continual direction.

Digital I/O: A type of I/O which can be either on or off.

Diode Rectifier: Similar to SCRs, but diodes do not have a gate and thus cannot be controlled. Diodes only allow the positive portion of AC power to pass through the converter. Most AC drives use diodes.

Dynamic Braking: A means of braking when a motor acts as a generator and the drive dissipates the excess current.

Enclosure: An outer covering that protects electrical devices that comprise the control aspects of the drive.

Encoder: A type of feedback device.

Feedback Devices: Sensors on the motor, or on a process line, that monitor actual performance.

Field Test: A means of determining the nature of the load, if it is not obvious.

Frequency: A reference to how often AC changes direction, and is measured in units of hertz (or cycles per second).

Harmonics: A special type of noise resulting from AC drives: sinusoidal waves with higher frequencies than the main power supply, which are transmitted back to the AC line.

Horsepower: A reference to how much work the motor can do, or how much torque it can deliver over time.

IEC: The International Electro-technical Commission, which writes international standards for electrical devices.

IEEE: The Institute of Electrical and Electronic Engineers, which is an association that writes standards.

Injection Braking: A means of braking an AC motor by using an AC drive to send DC voltage to the motor.

Insulated Gate Bipolar: A transistor used in AC drives to generate AC power Transistor (IGBT) from DC power through a control strategy called Pulse Width Modulation (PWM).

Inverter: A component of an AC drive that takes the regulated DC power and changes it back into a form of regulated (controlled) AC power.

Load Cells: A type of feedback device.

Load: The equipment being driven by the motor.

NEMA: The National Electrical Manufacturers Association, which creates standards primarily, followed in the USA.

Noise: Disruptions in a power or control system.

Open Loop Vector: A type of AC regulator that controls motor speed Regulator without feedback devices, regulates the current output to the motor, and controls the rotor/shaft speed by controlling the frequency of the magnetic flux in the stator.

Phases: A reference to how many currents (or voltage forces) are transmitted at one time.

Pulse Width: A control strategy which uses Insulated Gate Modulation (PWM) Bipolar Transistors to approximate an AC power supply by allowing variable amounts of DC voltage across the line.

Rated Current: The amount of current flowing through the drive/motor when under full load.

Regenerative Braking: A form of dynamic braking in which the power is dissipated back into the main AC line, rather than through resistors.

Regulator: The control portion of the drive that determines what voltage and current is supplied to the motor, and the circuit through which DC power is supplied to the motor.

Resistance: The “frictional” force in wires opposing the flow of current.

Rotor: The rotational part of a motor.

Shaft: The part of the rotor that extends outside of the motor case and connects to the equipment to be rotated.

Silicon Control: A gated diode that only allows current to pass Rectifier (SCR) through it when the current reaches a certain value, which turns on the SCR. DC drive converters typically use this device to transform AC current into a variable and tightly controlled form of DC current.

Stator: The stationary part of a motor.

Tachometer: A device that monitors the actual speed of the motor.

Torque: A reference to how much force the motor shaft exerts as it rotates.

User/Operator Interface: A means of allowing an operator to program control references to the drive/motor system, and to monitor motor and drive operating conditions.

Variable Torque Load: Loads in applications that exhibit both increases in torque and horsepower as speed increases.

Variable Voltage Control: A reference to DC drives because they manipulate the voltage supplied to the motor.

Voltage: The force that pushes or pulls electrons, causing them to flow.

Voltage Spikes: A type of noise in which large quantities are suddenly transmitted across the line.

Volts Per Hertz Regulator: A type of AC regulator which controls the frequency of AC power output to the motor, and does not use feedback devices.

ELECTRICAL MACHINERY

By: J. B. Calvert

The following are the ways electrical energy and mechanical energy are transformed into each other by rotating machines:

Rotating electrical machines – generators and motors – are devices that transform mechanical power into electrical power, and vice-versa. Electrical power from a central power station can be transmitted and subdivided very efficiently and conveniently. The operation of electrical machines is explained by four general principles that will be briefly presented below. These principles are not difficult to understand, and illuminate most of the reasons for the stages in the historical development of electrical power, and especially of electric railways. This section discusses motors in general, but the specific application to electric locomotives is emphasized. Electricity is the medium that carries power from the prime mover, whether at a central power station or on the locomotive, to its point of application at the rail, and allows it to be controlled conveniently.

Power is rate of doing work. One horsepower means lifting 550 pounds by one foot in one second. Mechanical power is force times speed. One watt is a current of one ampere (A) flowing in a potential difference or voltage of one volt (V). Electrical power is current (in amperes, A) times voltage (in volts, V). 746W is equivalent to 1 hp. A medium-sized electric locomotive might have a rating of 2000kW, or 2680 hp. At 85% efficiency, and a voltage of 15kV, 157A is drawn from the overhead contact wire. Torque is the rotational equivalent of force, often useful in speaking of motors. It is force times perpendicular distance, and power is torque times rotational speed in radians per second.

The first principle is that an electrical current causes a magnetic field which surrounds it like a whirlpool, and that this field, which is not material but rather a region of influence on other currents and magnets, is guided and greatly strengthened (by more than a thousand times) by passing through iron. When the current reverses in direction, so does the magnetic field. Currents deep in the earth cause its magnetic field, and the energy to drive them comes from either the rotation of the earth or the flow of heat within the earth. The field acts on the compass needle, which is a magnet. This principle can be called "electromagnet action".

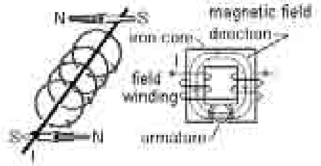
The second is that an electrical current in a magnetic field (produced by some other currents) experiences a force perpendicular to both the direction of the current and the direction of the magnetic field, and reverses if either of these reverses in direction. The force is proportional to the current and to the strength of the magnetic field. This principle can be called "motor action".

The third is that an electrical conductor, such as a copper wire, moving in a magnetic field has an electrical current induced in it. This is expressed by the creation of an electromotive force or voltage, which causes current to flow just as the voltage of a battery does. The effect is maximum when the wire, the motion, and the magnetic field are all mutually perpendicular. This principle can be called "generator action".

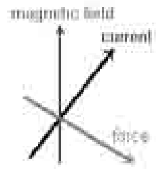
And the fourth principle is that a changing magnetic field causes a voltage in any circuit through which it passes. The change can be caused by changing the current producing the magnetic field, or by moving the sources of the magnetic field. This principle can be called "transformer action".

A rotating electrical machine consists of a field and an armature that rotate with respect to each other. The armature is the part of the machine in which the energy conversion takes place. The field provides the magnetic field to aid this process. In DC machines, the field is stationary (the stator) and the armature rotates within it (the rotor), because the rotation is necessary to switch the armature connections by means of the commutator, but it is only the relative motion that counts. In an alternator, the armature is stationary and the field rotates. The field consists of an iron core to carry the magnetic field, and a winding to excite the magnetic field by the current passing through it (first principle). The magnetic field is a passive but essential component in the operation of the machine. Like the field, the armature also consists of iron to complete the magnetic circuit, and is separated by a short air gap from the iron of the field. It is important that the air gap be as small as possible and remain uniform as the armature rotates.

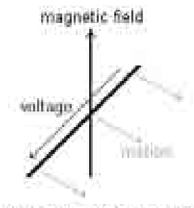
The armature also has windings. In a generator, these conductors are moved in the magnetic field producing a voltage (generator action). If a circuit is completed and current flows in these windings, a force is produced resisting the rotation of the armature (motor action) so that the driving machinery experiences a mechanical resistance and does work, which is being transformed into electrical energy. In a motor, these conductors are supplied with an electrical current, so that a force acts on them in the magnetic field (second principle), and this force can do external work. When the armature rotates while exerting the force, work is done, but a voltage is also produced opposing the applied voltage, resisting the flow of current in the armature (third principle), implying a change of electrical work into mechanical work.



Principle 1: a current creates a magnetic field surrounding it that is strengthened by passing through an iron core.

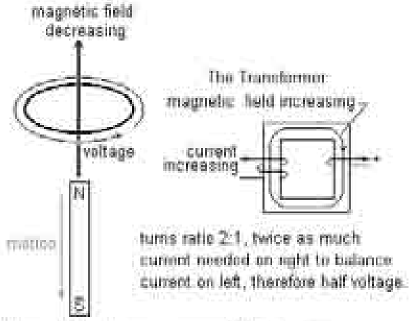


Principle 2: a force is exerted on a current in a magnetic field perpendicular to the plane of the magnetic field and the current.



Principle 3: a voltage is induced in a conductor moved in a magnetic field. Note that the voltage is opposit to the current causing a force in the direction of motion by Principle 2.

This opposing voltage generated when the armature of a motor turns is called counter-electromotive force. It might seem that it resists current flow through the motor, and of course it does, but it is really the essential factor in turning electrical into mechanical energy. Only the current that is driven into a counter-emf appears as mechanical work at the motor shaft; all else is wasted, the energy going into heat instead of mechanical work. Early inventors of electric motors did not realize this, and tried simply to get as much current into the motor as possible, which only burned the motor up without producing any mechanical effect.

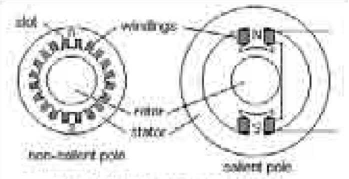

magnetic field decreasing
voltage
N
S
motion
The Transformer
magnetic field increasing
current increasing
turns ratio 2:1, twice as much current needed on right to balance current on left, therefore half voltage

Principle 4: a changing magnetic field induces a voltage however the change is produced. Only a change induces, not a constant magnetic field

Current is supplied to the armature through sliding contacts formed by graphite blocks (called brushes because originally brushes of phosphor bronze wire were used instead) pressing against copper rings. It is usually necessary to change the connections of the armature windings as they rotate with respect to the magnetic field, and this can conveniently be done by making the copper rings in segments. The result is the rotary switch called the commutator. These days, semiconductor switches can be used for this purpose in small motors, eliminating the commutator, but the principle is the same. The commutator and brushes are the only parts of a machine that normally require maintenance, except for the bearings and other mechanical elements. If it is not necessary to switch the current, as in AC machines, the moving contacts are called slip rings.

Contemplate now the complete chain of energy flow from the prime mover, a steam or internal combustion engine, to the point where the mechanical power is finally applied. The transformation at each end must take place with a smooth mutual reaction, based on the second and third principles. This was not properly understood until the 1880s, so that practical electric transmission of power was delayed until that time. Power that is not delivered to the load is lost as heat in electrical resistance, which is equivalent to mechanical friction. Heat is produced in the generator, transmission lines, and motor, and limits the amount of power that can be handled.

The ways that windings of wire are arranged in modern machines are shown below. The windings are either around the pole pieces, or placed in slots on the surface. The part that rotates is called the rotor, and the part that remains at rest is called the stator. Both are of a magnetic core iron alloy, and are laminated if they are subject to alternating magnetic fields, to reduce eddy-current losses. DC machines typically have a salient-pole field on the stator, with the field windings on the pole pieces, and a non-salient pole winding on the armature, forming the rotor. The magnetic field of the stator is constant, while the field in the armature alternates. Therefore, the armature is laminated. The actions of salient and non-salient pole windings are equivalent. A non-salient pole winding can be arranged to give any desired spatial distribution of magnetic field. The typical salient-pole winding of a DC machine provides field-free regions between the poles that aids commutation, since switching can be done while the armature conductors are in this region and not generating any emf. In both salient and non-salient pole machines, the windings are firmly held mechanically.



two poles only shown; N and S poles alternate if more than two poles

Arrangement of Windings

The windings of motors and generators can be connected in one of two basic fashions. If the field windings and the armature windings are in series, they are called series-connected. In this case, the field windings are of heavy-gauge wire to carry the main motor current. The field becomes stronger as the armature current increases, leading to a very great force at low speeds. If the field and armature are in parallel, they are called shunt-connected. The field winding consists of rather fine wire. If the voltage applied to the motor is constant, then the field strength is also constant. If a generator is rotated at constant speed, then the output voltage is independent of the load. There are intermediate cases where the field has both series and shunt windings, and such machines are called compound.

Most direct-current power-station generators are mainly shunt-connected, and most traction motors mainly series-connected, as you might expect from the requirements of the two services: constant voltage in the first case, high starting torque in the second. Rotating machines can be made for voltages up to about 2000V, the restrictions being insulation and flashover at the commutator.

It is not easy to change DC voltages. One way to do this was to use a dynamotor, which had a normal field winding, but dual armature windings and two commutators. One winding was supplied at the input voltage and drove the dynamotor by motor action. The other winding supplied the output voltage. This can really be considered a kind of AC transformer. The input commutator creates AC from DC, and the output commutator changes the new AC voltage to DC. In World War II, when radios required a plate supply of, say 300 V, dynamotors were used to obtain this voltage from 6 V battery supply.

The speed of a direct-current motor is determined by both the field strength and the load. If there is no load, the speed is such that the voltage produced in accordance with the third principle exactly balances the applied voltage, and the armature current is zero. As the load is increased, the speed decreases to allow current to be drawn so the necessary electrical power can be converted. When the motor stalls, it is exerting its maximum force. Therefore, the speed of a shunt motor, or one in which the field is produced by a permanent magnet, is determined by the applied voltage, and can be adjusted finely.

If voltage is applied to a series motor without a load, the motor speeds up. As it does so, the field current decreases so the motor must speed up some more to generate the same back voltage. This keeps up until the motor flies apart. The loss of load on a series motor is a serious thing and must be guarded against. When a loaded series motor is rotating with the maximum voltage applied to it, the current just produces the required amount of force with the existing field strength. If the field is weakened by reducing the current in it (by putting a resistance in series with it, for example) the motor must speed up to compensate. This is one method of speed control for direct-current motors.

A large direct-current motor must not be started by applying the full voltage across it while it is at rest, especially a series motor. The heavy current and field will create a great jolt that may damage the motor and its mechanical connections. A starting resistance is used to limit the initial current to only the amount necessary to put the motor into rotation. As it speeds up, the starting resistance can be removed in steps. In normal operation, the starting resistance should be removed, since it represents a significant loss of power. For further speed control when more than one motor is used, as on a streetcar or locomotive, the motors can be connected in series to start, and in parallel to run. In each case, the field can be weakened to give a higher speed. With four motors, series, series-parallel, and parallel connections, with field weakening, gives six speed levels that can be designed for service requirements. This could give, for example, speeds of 10, 15, 20, 30, 40, and 60 mph with starting resistance switched out.

A direct-current motor can be reversed by reversing the direction of the current in either the field or the armature. There is more to the story, however. The small demonstration locomotive of Werner Siemens of 1879 reversed by means of gears, and some authors have implied that it was not yet known how to reverse a DC motor, which is absurd. The problem lay in the brushes and commutator. The brushes must be placed so that their switching action takes place at the moment when the current in the windings being switched is zero. As the load on the motor increases, the armature current increases, and the magnetic field it produces causes the total magnetic field to change so that the brushes must be shifted to a new point of zero current. If this is not done, there is sparking at the commutator, which is rather destructive. The brushes on Siemens' locomotive were set at an average position for the load, so that if the motor were reversed, the brushes would have been at an improper position, and sparking would result. Therefore, he used reversing gears and the motor continued to rotate in the same direction.

A better way out of this difficulty was soon found. Small poles, called commutating poles, were placed between the main field poles. These windings are in series with the armature, and proportioned so that they cancel the varying field of the armature. The optimum brush position then becomes independent of motor load or direction of rotation.

Semiconductors have made possible a continuous control of voltage to the traction motors. This is called chopper control, and gives direct-current locomotives the same fine speed control as alternating-current locomotives. Using semiconductors, direct-current electrification is possible without any rotating machines, and all the advantages of both alternating and direct currents can be exploited.

If a commutator is not used on a generator, merely slip rings to connect with its windings without any switching, its output voltage alternates smoothly from positive to negative, which can be made to be a pretty good sine curve by using non-salient-pole windings. It is easier to generate such an alternating current by rotating the field inside a stationary armature, so that the main current does not have to flow through the sliding contacts. The sliding contacts, which are called slip rings, need handle only the lower voltage and current of the field windings. High voltages can be generated because it is much easier to insulate the stator, and because these voltages do not have to be handled by the slip rings. This is such an advantage that practically all electricity is generated as alternating current, and the generators are called alternators. These advantages were even reflected in automobiles, which previously used 6V dynamos, but now all use 12V alternators. Typically, the stators are non-salient-pole, while the rotating fields have salient poles.

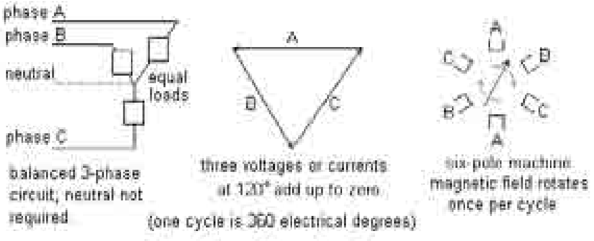
Alternating current has the compelling advantage that its voltage can be changed easily and efficiently by a transformer, which is a closed iron core surrounded by two windings (first and fourth principles). The ratio of the voltages in the two windings is the same as the ratio of the number of turns, and the ratio of the currents inversely, so that the power remains the same. Since there are no mechanical parts, the efficiency of transformers is very high, and maintenance very low. Alternating current is transformed to higher voltage and smaller current for transmission, and back to lower voltages for use. Transformers with taps can be used to obtain a series of voltages if desired. In fact, an almost continuous voltage variation without loss is possible.

If direct current is required for motors, alternating current can be converted to direct current in four ways. First, a motor-generator set can be used, running at constant speed. A better solution is the rotary converter, essentially a DC generator rotated by AC supplied to it. These were the only practical ways at first for large power requirements, especially for electric railways. Later, rectifiers based on electrical discharges, notably the mercury-arc rectifier, made conversion possible without rotating machines, and with currents appropriate for locomotives. Both of these methods have now been completely superseded by solid-state (silicon) rectifiers, which are trouble-free and easily controlled. Single-phase 50/60 Hz alternating current can be supplied at high voltage, reduced in voltage by a transformer, rectified by solid state rectifiers, and applied to direct-current traction motors, making a very serviceable and economical locomotive that is today's standard.

The Ward-Leonard system of speed control for a direct current motor used a generator driven by a motor supplied from any kind of current, alternating, three-phase, or direct. By control of the generator and motor fields, control of the motor over a wide range of speeds was possible. This system was used in a few locomotives to permit the use of direct-current traction motors with single-phase alternating current supply. The problem was that three machines of equal capacity were required in place of one, a very costly alternative. Semiconductor rectifiers or chopper control have completely replaced the Ward-Leonard system.

At first sight, it would seem easy to make alternating current motors. If the polarity of the supply to a DC motor is reversed, the motor continues to turn in the same direction. If AC is supplied, the torque might be pulsating, but at least it would always be in the correct direction. Unfortunately, this is not true (except at unrealistically low frequencies) because of the existence of reactance that causes phase differences and inductive kicks. The magnetic fields and the currents get out of register, torques are small, and there are sparks everywhere. However, with the series motor there is some hope, because the same current that creates the field also passes through the armature, so they must stay in phase. In fact, series motors can be designed for AC, and they have been brought to a high state of excellence, although best at 16 2/3 or 25 Hz.

Most AC motors, however, depend on a rotating field produced in the stator, or stationary part of the motor. This is a magnetic field produced by windings through which alternating currents are passed that seems to rotate around the stator with time. The number of poles P is the number of north and south poles around the circumference, and is determined by how the windings are placed on the stator. The rate of rotation of the field is given by N = 120 f/P rpm, where f is the frequency of the alternating current. A four-pole field rotates at 1800 rpm, for example, with 60 Hz current. This is called the synchronous speed. The easiest way to produce such a field is to use an AC supply that consists of several voltages with a constant phase difference between them, called a polyphase supply. One could use two voltages at 90° phase difference, and let each voltage supply alternate coils in a four-pole machine. Better, however, to use three voltages at 120°, called three-phase, for then the power flows as evenly as with DC. These voltages are generated by separate windings on the alternator, and are supplied over three wires. These stators have no salient poles, but have a smooth surface with the windings embedded in slots. Three-phase current is normally used for transmission and distribution of electrical power, since it is the most efficient means in terms of the copper required and transmission losses.


phase A
phase B
neutral
equal loads
phase C
balanced 3-phase circuit; neutral not required
A
B
C
three voltages or currents at 120° add up to zero
(one cycle is 360 electrical degrees)
A
B
C
A
B
C
six-pole machine magnetic field rotates once per cycle

Three Phase Alternating Current

Suppose we have such a stator with a rotating magnetic field. For the armature, we use a drum armature as for a DC motor, but simply short-circuit the windings. Then, when the motor is not rotating, we have what is very much like a transformer with a shorted secondary winding. It is excited at the frequency of the stator currents. Unlike a transformer secondary, this secondary can rotate in response to the forces exerted on it (its windings are in a magnetic field). When it does so, it tends to follow the rotating field more and more closely. When it is rotating at exactly the same speed as the rotating field, the apparent frequency to the rotor is zero, and no currents are induced at all. If it rotates slightly slower, or slips, the frequency increases, and more currents are generated. The slip is the difference in rotating speed divided by the synchronous speed, expressed as a percentage. The forces on these currents provide the torque exerted by the motor. The torque increases about proportionately to the slip. At some point, however, the reactance of the armature windings comes into play not only to limit the currents, but to move them out of phase with the magnetic field. So the torque levels off, and passes a maximum value called the breakdown torque. The motor now slows down more and more rapidly, the torque more and more out of phase. When the rotor comes to rest, the starting torque is produced, and the motor will not move until the required torque is less than this amount.

This kind of motor is called an induction motor, which has no DC analog. It rotates a bit more slowly than the speed of the rotating stator field, which is called the synchronous speed. Large polyphase motors may have a slip of only 1% or so at normal load, so the induction motor is essentially a constant-speed motor. Its speed can only be greatly changed by changing the frequency of the supply. The starting torque is considerable, but at the cost of rather high currents out of phase with the voltage. The lagging power factor of an induction motor can be a problem. Nevertheless, the lack of a commutator and brushes, and that it has a reasonable starting torque, make the induction motor the most commonly used AC motor. A typical motor has a rotor composed of parallel thick copper or aluminum conductors connected to a ring of the same material at the ends. This is called a "squirrel cage" rotor.

Squirrel-cage rotors, because of their low impedance, run with small slip and give high torque at speed. However, their starting torque is poor. If your sink garbage disposal is on the same circuit with some lights, note the lights dim briefly when you switch it on. This is the result of the high reactive current drawn by the static induction motor, which can be 4 times the normal load current. Fuses must be slow-blow to let this pass before deciding that there is some problem. There is usually a circuit breaker on the disposal that opens if the motor is stalled. You might also note the limited starting torque when the motor fails to start if it gets something in its teeth. By adding resistance to the rotor, better starting torque can be obtained, at the cost of poorer running at speed. Ways have been devised to cut out the resistance after starting, but these involve a wound rotor with brushes, or complicated double windings, and have not been worth the bother.

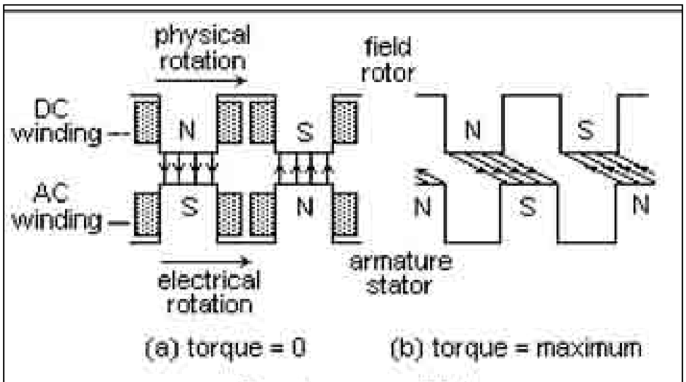
Small single-phase induction motors can be made that create the extra phase that is necessary for starting the motor internally. Examples are the split-phase, capacitor start and shaded-pole motors used on motors of a few hp and less. Split-phase motors use a separate winding of higher inductance to produce a phase shift; capacitor motors use a capacitor for the same effect, and the capacitor can be switched out after the motor has started and has come up to speed. A shaded-pole motor has a copper ring around one side of the poles to retard the flux there, so the field appears to rotate. These single-phase motors can operate on 50/60 Hz, but are not suitable for traction motors because of their poor starting characteristics, and their low efficiency.

An unusual type of single-phase AC motor has non-salient-pole stator and rotor. The stator is supplied by the single-phase AC current, while the rotor is very similar to a DC armature, with commutator and brushes. The brushes are short-circuited, and the armature current is created by induction from the stator. If the brushes connect turns that are in field-free regions, any armature current would be in phase to produce a torque. However, with this brush position, there is no current, since the emf's cancel. If the brushes connect turns that are under the poles, the induced armature currents are a maximum, but the forces exerted on them cancel. At some intermediate brush position, there is both current and a net force. The motor can be reversed by moving the brushes past a pole to an equivalent position. Such a machine is called a repulsion motor, and it acts somewhat like a series motor. Although it gives good torque, commutation at the brushes can be difficult, with sparking. The theory of the repulsion motor is rather difficult.

A non-salient-pole stator with a rotating field can be used with a salient-pole rotor to make an AC motor. This is, in fact, exactly like an alternator except that the mechanical power is output, not input. The rotor is fed DC by slip rings to magnetize it. As the stator field rotates (electrically), it will carry the rotor poles around with it at the synchronous speed (mechanically). For this reason, this type of motor is called a synchronous motor.

A synchronous motor is essentially an alternator run backwards. Rotor current must be supplied, because there is no relative motion to induce it as in an induction motor. The magnetic field in the rotor is constant, and corresponds to the constant flux in a transformer. However, its alternating variation as seen by the stator windings is now produced by its motion.

A few poles of a synchronous motor are shown in the diagram below. Stator poles are shown as salient for clarity, though the stator is usually non-salient-pole. The rotor and stator poles remain in fixed relative positions. The rotor poles are carried along by the rotation, while the stator poles move as they are excited by the polyphase supply. When there is no torque exerted by the rotor, conditions are as in (a). When the motor supplies a torque, the rotor lags a bit behind, as shown in (b). The lines of force suggest the pull on the rotor, since there is a tension along the magnetic field. There is now a phase difference between rotor and stator, inducing a voltage that reduces the back emf presented to the supply, and the current to the motor stator, in phase with the voltage, must increase to bring the back emf up to the supply voltage, exactly as in a transformer. It is rather difficult to see this except by a detailed analysis involving phasor diagrams, but the force and energy relations can be verified as for a DC motor. Energy supplied against a back emf is transformed to an equal amount of mechanical energy.



Synchronous Motor

The motor torque depends on the angle the rotor lags behind the rotating stator field. If the torque required is too high, the motor may drop out of synchronization, and then come to rest. Such motors can supply considerable power, but run at a fixed speed determined by the current frequency, and cannot start against a load. They may be started by an auxilary motor, by acting as an induction motor, or by other means, before load is applied. They are, therefore, unsuitable as traction motors, but can be the motor in a motor-generator set. They can drive a three-phase alternator in this arrangement, which can feed three-phase traction motors, or, of course, can drive a direct-current generator, as in a Ward-Leonard control. The synchronous motor requires DC excitation, and has slip rings to maintain, so it is not as commonly used as the induction motor. If the DC field excitation is changed, the synchronous motor can be made to draw reactive, wattless quadrature current and act as a capacitor or an inductor. Only for a certain level of excitation is the current in phase with the applied voltage. Synchronous motors without a mechanical load can be used to correct power factor in a transmission system.

One type of small synchronous motor is used to drive clocks. Tesla chose 60 Hz as the power frequency looking toward this application. More useful for this purpose are subsynchronous motors, that run at a fraction of the synchronous speed, making the gearing easier. These motors can have a toothed rotor, or a rotor consisting of copper rods, and will lock in at a subsynchronous speed, though they are fundamentally two-pole motors operating at 3600 rpm. Such motors cannot supply much torque.

A synchronous converter can convert AC to DC with high efficiency. This is a machine much like a DC generator, but with a polyphase non-salient-pole field. Polyphase, usually six-phase, power is supplied to the stator, while the rotor rotates at the synchronous speed. DC can now be taken from the commutator and brushes. The armature current is the difference of the AC and DC currents, so it is rather small and this helps the efficiency of the machine. The DC side of the machine can be used to bring it up to synchronous speed quite conveniently, if DC is available from batteries or some other source. Synchronous converters were much used before solid-state rectifiers became available.

Quite recently, semiconductors have made possible the creation of three-phase power of variable frequency, so that it becomes applicable to traction motors. Electrical power generated by an alternator, or supplied by a contact wire, is first converted to direct current, then to variable-frequency three-phase for supplying induction traction motors in a locomotive. In this way, commutators and other troublesome sliding contacts are completely eliminated, reducing maintenance costs. This has occurred even though DC has distinct advantages for traction.

Improvements in motors since the turn of the century, making them smaller, lighter, and more efficient for the same output, have been due to three main factors. The first was rational design of the magnetic circuit, to make the best use of the iron. Next was improved magnetic material, especially silicon iron with low losses, that meant less iron could be used and motors could be more compact. Finally came better insulating materials that required less room and could stand higher temperatures. These benefits extended to all other electrical machinery as well, including generating apparatus and transformers.

A supply in the range 600-700V DC was common for street railways, rapid transit, and interurban electric railways, in spite of the heavy currents required. Remember that power is voltage times current, so doubling the voltage halves the current for the same power, and the losses are proportional to the square of the current, so a decrease in current is very desirable. A voltage much above this cannot safely be used for third rails and where work must be done around energized equipment. With normal precautions, such voltages are not fatal and require actual contact for danger. 1500V was initially popular for main line electrification with an overhead contact wire. Somewhat higher voltages, up to 3000V, were later used to reduce the traction currents as far as possible, although 3000V generally requires traction motors to be permanently in series. 11, 15, and 20kV are used for alternating-current electric railways using an elevated contact wire. These are the highest voltages that can be safely used taking normal clearances into account. Personnel must be kept well out of the way of such voltages, which, unlike the lower voltages just mentioned, can reach out and be fatal at considerable distances. Transmission may be at 100kV and over, where the conductors are specially insulated on high towers.

Although we have seen a bewildering variety of rotating electrical machines, there is really only one fundamental principle at work. These machines are transformers between electrical and mechanical energy, just as the usual AC transformer transforms between electrical energy at different voltages. In fact, the ordinary transformer was also called a static transformer. These machines are dynamic transformers. On the mechanical side, the energy is transmitted by rotation. Torque times angle is work, torque times angular velocity is power. Every machine has a magnetic circuit, in which certain fluxes are established that are analogous to the flux in a static transformer. This magnetic field assists in the energy transfer, but does not receive or give energy itself. The magnetic flux links conductors, and can exert forces on them if they carry currents, and can induce emfs in them if the flux changes. The forces determine the mechanical power, while the emfs determine the electrical power. There are other energy effects, such as I2R loss in the conductors and the eddy currents, iron losses due to hysteresis, mechanical friction and windage, and the alternating flows of reactive volt-amperes. However, the induced emfs and the forces are always such as to represent an ideal conversion between electrical (emf times current) and mechanical (force times distance) energy, accompanied by these losses, which can be minimized, but are unavoidable.

When the conductors are on the surface of the rotor, actually in the magnetic field of the air gap, it is easy to see how the emf is induced, and how, if current flows, the force times distance equals the emf times current, as we pointed out at the beginning of this paper. It is not so easy to see this if the windings are on the stator, while the force is on the rotor, and if the conductors are buried in the iron, or wrapped around the poles. Nevertheless, a careful analysis would show in every case exactly the same relations that are so evident with conductors in the air gap.

To generate electrical energy, we move conductors (armature) in a magnetic field (field) at rest, or else move a magnetic field (rotor) relative to conductors at rest (stator). In either case, we get a periodically reversing emf that can be made sinusoidal by careful design. If generated in the rotor, the motion can be used to switch the connections so that the output current is unidirectional, and more or less constant. Mechanical energy always enters by the rotor, but electrical energy can be taken either from the rotor or the stator. Whenever any current is drawn, the mechanical side feels the effect as an increased drag. The energy received from the mechanical side is always greater than the electrical energy delivered.

To generate mechanical energy, we can place movable conductors (armature) in a steady magnetic field (field). Torque is produced when we drive a current through the conductors, and when the armature moves, we feel an electrical opposition to supplying the current. Or, we can wind the stator to produce a rotating magnetic field, and have this field drag along conductors on a rotor. Current is driven through the rotor conductors either by induction, or by an external source. In either case, when mechanical energy is drawn, there is an electrical effect amounting to an increase of the current driven into a back emf. The energy delivered to the mechanical side is always less than the electrical energy supplied.

The only general and satisfactory way to understand the forces on the rotor of an electrical machine is by considering the magnetic field over an imaginary surface surrounding the rotor. Electric fields play no role in the forces in electrical machinery. From the magnetic field, the Maxwell stress tensor can be found, and from it the forces on the rotor, by integrating the shearing stresses over the surface. In the usual DC motor, if no armature current exists, the magnetic field passes symmetrically through the armature, and there is no net torque on it. When armature current flows, it creates a transverse component of the magnetic field, so the total field is “twisted”. This field has a tangential component in the air gap that is responsible for the torque on the armature. The picture of current-carrying wires in a magnetic field is of little help in understanding an actual motor.

Rotary motion is ideal for most applications. On the mechanical side, it allows the use of an excellent and efficient mechanical transformer, gearing. Bearings provide a convenient support for rotating shafts. Turbines provide rotary power for generators, and they are efficient prime movers when used at constant speed and constant power. Just as there are reciprocating engines, one can conceive of reciprocating electrical machines. However, one notices that reciprocating motion usually has to be transformed to rotary motion for applications, aside from such things as driving a reciprocating pump. Even here, the centrifugal pump, with rotary motion, is used where possible. Reciprocating electrical machines have been tried, but were very unsatisfactory, and there is no reason to resurrect them. Motors with a linear stator would also seem quite impractical mechanically, if not electrically. The only application would be to traction, but here they are a solution without a problem. Professor E. Laithwaite of Imperial College promoted linear motors vigorously, and there are still efforts in this direction, usually with magnetic levitation as well. The best use of this idea would be if the power were supplied to the stator, with a passive “cursor”, but this would be hopelessly uneconomic for practical transport, though feasible for very short distances. There is no essential difference in operation between these linear motors and the rotary ones.

ENERGY SAVING SYSTEMS FOR INDUCTION MOTORS

Are they a sham? Do they work?

By: T.M.Empson

There seems to be a resurgence in interest in the Nola energy saving algorithm for induction motors, with a number of manufacturers beginning to market "new" and "improved" versions of this technology.

The technology was originally proposed and developed by Frank Nola of NASA in the mid to late 70s as a means of reducing energy wastage on small single-phase induction motors. From the initial NASA developments, we saw a number of manufacturer's world wide gaining manufacturing rights and marketing the technology in various forms. Difficulties were experienced in the early days in applying this technology to three-phase motors in a fashion that they would perform with stability and reliability.

Many patent applications were made in the early 80s covering variations in the technology as it could be applied to the three-phase applications. An early application by Rutherford and Empson was successful in both operating as specified and in being granted letters patent. Many of the other early three-phase patent applications were purely speculative and could not possibly achieve the desired results.

The concept of energy saving has always been an attention grabber, especially when the promised savings are high and the potential for a reduction in running costs appears high. The initial introduction of this technology was a marketing person's dream, and some very extensive marketing plans were implemented in the early 80s. Unfortunately, the marketing was based on the results achieved with very small machines, and expectations were high because of the results so achieved. There were many promises made to prospective users based on extrapolated data which was not field verified at an early stage, and could not be realized in real applications.

As we experienced in the early eighties when we were manufacturing similar products, there appear to be many misconceptions about the performance of induction motors and many claims are based on the presumption that the induction motor at less than full load is an inherently inefficient device. We withdrew from promoting this type of device as a result of expectations in the marketplace that resulted from overzealous marketing with totally unrealistic claims which could not be achieved without inventing perpetual motion. – I recall a refrigeration engineer who had been promised a 50% energy saving on his 50KW refrigeration units which were constantly running at about 50% load. He had tried numerous units to no avail, and eventually approached me on a recommendation. I asked him for the efficiency of the motors at this load and he found that it was about 87%. As he immediately began to see, there was no way that he could save 50% of the energy consumed by the motor. To do so would require a motor efficiency of over 100% which is just not possible with an induction motor and today's technology.

There is no doubt that under the right conditions, technology can reduce the energy drawn by an induction motor, and thereby achieve some benefit. The problem is that, as the result of limited technical understanding of the induction motor and its characteristics, erroneous claims are being made by extrapolation of results achieved with small motors. Worked examples often show flawed methodology in making power measurements in three-phase three-wire installations.

1. THE TECHNOLOGY

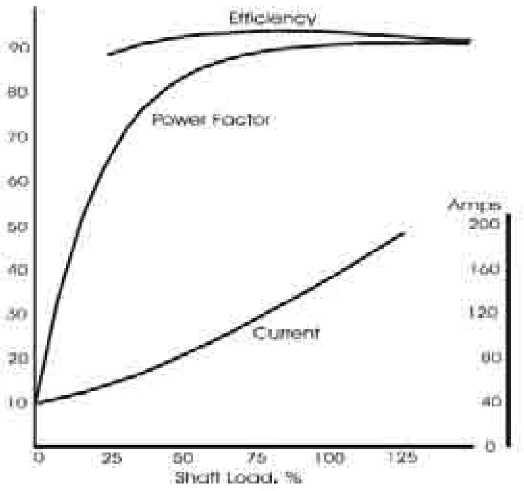
The basic algorithms are proposed by Frank Nola 20 years ago to monitor the power factor of the motor, and to reduce the voltage when the power factor is dropping in a manner as to increase the power factor. There is a correlation between the power factor of the motor and the motor efficiency such that the power factor will begin to fall when the efficiency of the motor falls. As such, the energy saving algorithm will act to improve the motor efficiency by reducing the iron loss in the motor. In some cases of very lightly loaded motors, it will also reduce the magnetizing current and where this is much greater than the work current, the copper loss may also be reduced. Although there may be some slight differences in the way the modern algorithm is implemented, I do not believe that there can be any significant improvement in the energy savings experienced in the early days when we were experimenting with this type of product. We found that the limitation was not the controller, but the inherent efficiency curves and characteristics of induction motors.

2. INDUCTION MOTORS

Large induction motors are inherently very efficient with efficiency figures as high as 95% at full load being quoted. The efficiency will fall at reducing load, however the efficiency only falls by a small margin between full load and half load. For example, a Brook Crompton 110Kw motor type 7GUD315S is rated at 92% efficient at full load, 91% efficient at three quarter load and 89% efficient at half load. As the shaft load is reduced, the current reduces, reaching a minimum of the magnetizing current of the motor. The magnetizing current for an induction motor can vary between 20% of the rated full load current and 60% of the rated full load current of the motor depending on the motor design. As the load is reduced, the power factor of the motor also reduces by a small margin. With the Brook Crompton 110Kw motor, the power factor at full load is quoted at 0.92, three quarter load is 0.91 and at half load is 0.88. In this example, the potential energy saving at half load is very small. It is probably not unreasonable to expect that the maximum efficiency of a given induction motor is not going to be much in excess of its rated full load efficiency, so a half load efficiency gain of 4% may be achievable under ideal conditions, but with the non sinusoidal currents created by the use of an energy saver, this is not achievable in practice.

Induction motors have five major components of loss; Iron loss, Copper loss, Frictional loss, Windage loss and Sound loss. All these losses add up to the total loss of the induction motor. Frictional loss, windage loss and sound loss are constant, independent of shaft load, and are typically very small. The major losses are Iron loss and Copper Loss. The iron loss is essentially constant, independent of shaft load, while the copper loss is an I2R loss which is shaft load dependent. The iron loss is voltage dependent and so will reduce with reducing voltage.

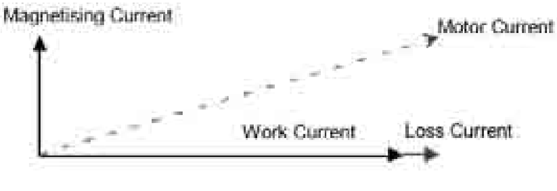
For a motor with a 90% full load efficiency, the copper loss and iron loss are of the same order of magnitude, with the iron loss typically amounting to 25-40% of the total losses in the motor at full load. If we consider, for example, an induction motor with a full load efficiency of 90%, then we could expect that the iron loss is between 2.5% and 4% of the motor rating. If by reducing the voltage, we are able to halve the iron loss, then this would equate to an iron loss saving of 1-2% of the rated motor load.



Toshiba 90KW 4pole motor

If the motor was operating under open shaft condition, then the power consumed is primarily iron loss and we could expect to achieve a saving of 30%-60% of the energy consumed under open shaft conditions. It must be reiterated, however, that this is only about 1-2% of the rated motor load. For example, if we take a Toshiba 2 pole 22kW D180M motor, we find a full load efficiency of 90.9%. This motor has a rated iron loss of about 25% of the total loss. This amounts to 22 x .091 x .25 = about 500 watts. At best, I would expect to halve this loss, resulting in a saving of 250 watts at light load. Under open shaft conditions, this may well amount to 30% of the energy consumed by the motor, but it is still only about 1% of the motor rating. If the energy wasted by the motor is small, then there is very little to be saved, irrespective of the technology used.

The current flowing into an induction motor comprises three major components, magnetizing current, loss current and load current. The magnetizing current is essentially constant, being dependent only on the applied voltage. The magnetizing current is at phase quadrature to the supply voltage and so does not contribute to any Kw loading except for the contribution to the copper loss of the motor. The magnetizing current causes a reduction in the power factor seen by the supply. The loss current is essentially a Kw loading as is the load current. For a given shaft load, the output Kw must remain constant. As the terminal voltage of the motor is reduced, the work current component must increase in order to maintain the shaft output power. (P = I x V) The increasing current resulting from reducing voltage can, in many instances, result in an increasing I2R which is in excess of any iron loss reduction that may be achieved. For a large motor, the magnetizing current can be as low as 20% of the rated full load current of the motor.



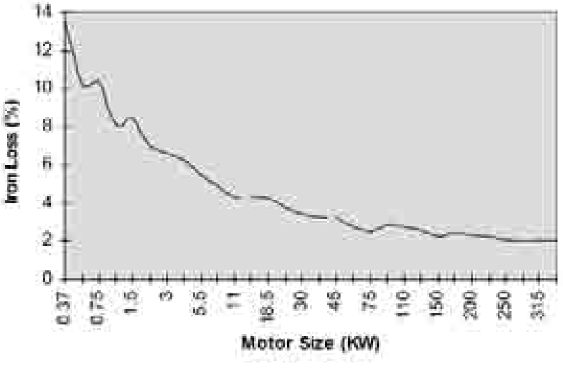
Three-phase induction motors have a high efficiency to less than 50% load, and experience suggests that there is no realizable saving to be made until the motor is operating at well below maximum efficiency (typically below 25% load). A Toshiba 150KW 4 pole machine exhibits a full load efficiency of 94.6%, 75% load efficiency of 94.8%, 50% load efficiency of 94% and a 25% load efficiency of 90.3%. There are many examples such as this which illustrate that the induction motor is efficient at considerably less than full load and, as such, there can be very little advantage in using an energy saving algorithm on anything other than a small inefficient motor. Using SCRs to reduce the voltage applied to an induction motor operating at reduced load and a high efficiency will reduce the iron loss, but there will be an increase in current to provide the work output. This increase in current will increase copper loss by the current squared, offsetting and often exceeding the reduction in iron loss. This will often result in an increase in the total losses of the motor. i.e. will have the reverse effect to that for which it was installed. The potential to save energy with a solid state energy saving device only becomes a reality when the motor efficiency has fallen. This generally requires a considerable fall in power factor, typically down to below 0.4 under full voltage operating conditions.

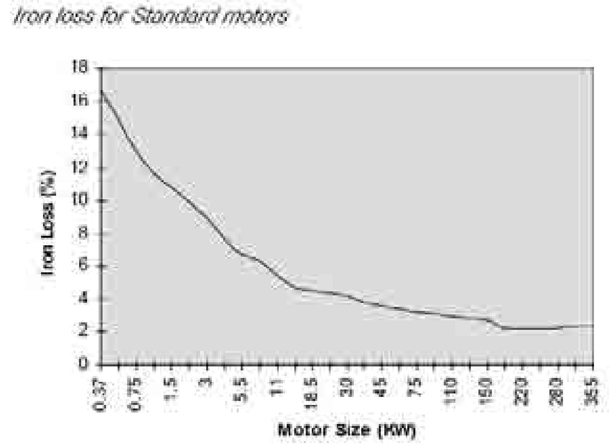
Large motors have a very low iron loss, (often 2-6% of the motor rating) and, so, the maximum achievable savings are small relative to the motor rating.

Three phrase 4 pole toshiba motors

KW	0.37	0.75	2.2	5.5	11	30	110	355
eff	66.2	74	82.5	86.4	89.2	91.6	93.2	94.9
pf	0.69	0.83	0.84	0.85	0.86	88.7	0.91	0.88

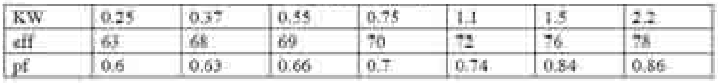
Iron loss for Energy Efficient Motors.





Very small motors, (particularly-single phase motors) have a much lower efficiency, and a much higher iron loss and so the potential to save energy is considerably higher.

Single phase motors



KW	0.25	0.37	0.55	0.75	1.1	1.5	2.2
eff	63	68	69	70	72	76	78
pf	0.6	0.63	0.66	0.7	0.74	0.84	0.86

3. MEASUREMENT TECHNIQUES

To establish the energy saved in a given installation, it is important to ensure that the measurement techniques are appropriate and correct. Three-phase Induction motors are a three-wire circuit with a power factor which can vary between 0.1 and 0.95. Three-phase power measurement techniques must be employed in order to achieve meaningful results. The standard methods of measuring the input power on a three-phase three-wire circuit are either to use the single-phase watt meters, one per phase and sum the results, or use the two watt meter method, or a three-phase watt meter. Measurements made on one phase, and multiplied by three can be extremely erroneous, especially under light load conditions. The Kilowatt loading on the three phases at light loads can be severely unbalanced even though the currents may not be unbalanced to the same degree. When using the two watt meter method, care with phasing is very important as this can totally alter the results. Measurements made by multiplying voltage, current and power factor on each phase can work with a continuous sinusoidal current provided that each phase is individually measured, and the power consumption from each phase is then summed to give the three phase power consumption.

Measurements on non-sinusoidal currents and or voltage must be made with true integrating watt meters. The formula of P = V x I x pf applies only with a continuous sine wave current and voltage. The introduction of SCR or triac switching elements into the circuit to control the voltage results in non-sinusoidal current and voltage, and under these conditions current, voltage and power factor measurements are meaningless in determining the power consumed. By definition, power is the integral of instantaneous volts x amps of the period of one or more cycles. At the instance that current is flowing, the SCR or triac is turned ON resulting in full line voltage at that instance in time. Therefore, there is no difference between measurements made on the input of the energy saver or the output of the energy saver with the exception that there is some loss in the energy saver which will appear on input measurements but not output measurements. There is no way that the power consumed by the motor can be measured or approximated by measurement of the current in one phase, the power factor, and the output voltage applied to the motor, all multiplied together. This results in totally fictitious results.

Comparisons are best made under controlled conditions with a true Kw or kWh metering system. The rotating disk kWh meter is what the power bill is based on and so it is a good instrument to use.

4. CLAIMS

A recent review of yet another newcomer onto the international market with an energy saving device for induction motors showed the same inaccuracies and misrepresentations that were common when the technology was first promoted. The information given displays a number of inaccuracies which severely compromise the credibility of the claims that are made. The statement is made that:

> "Induction motors draw the same current whether loaded or unloaded; the efficiency goes down when less than the rated load is applied to the motor." This statement is demonstrably incorrect and is the foundation of the basic assumption that motors operating at half load will save up to 50% percent power consumed. This statement was contradicted in the same literature by the statement that: "the current at half load was about 75% of the full load current." This statement would be true on a small single phase motor with a magnetizing current in the order of 50% of the rated full load current, or higher.

Another statement that, "the company believes that it was the first to develop and introduce an energy savings device utilizing digital technology." The company is somewhat ill informed as companies such as Fairford had micro based energy savers available more than 16 years ago. Rockwell have had one available for a number of years also.

Many of the test results, quote irregular results such as induction motors with power factors as high as 0.99 and power factors that drop as the voltage is reduced when, in fact, the algorithm works by reducing the voltage to maximize the power factor. One report shows a "voltage saving of 10.7% and a "current saving of 13.0%" resulting in a "KVA saving of 23.7%". This is absurd and suggests that other figures are also incorrect. In reality, the current only flows through the triac while it is turned on, so the current must be multiplied by line voltage to give the correct results. This can be verified by the use of true power board type metering. The true saving is more like 13% KVA.

A detailed look at the quoted examples of energy saving is quite alarming, as the quoted results are obviously not correct.

In one such quoted example, the application was for a Chilled water pump 75Hp, 95 Amp, 440V 3ph.

Tests were quoted as below:

Without energy saving device	
volt	479
amp	68
kw	32
kva	33
pf	1.0

Immediately there are some anomalies here:

a) A three-phase motor drawing 68 amps at a line voltage of 479 volts would be drawing P = V x A x pf x Å3 = 479 x 68 x 1 x 1.732 = 56KW. Where did the 32 KW come from?? 32 = 479 x 68 x 0.98. (line voltage times current times power factor).

b) The KVA drawn by a three phase load is equal to V x A x Å3. In this case, the KVA demand would be 479 x 68 x 1.732 = 56KVA, not 33 KVA as quoted.

c) Induction motors never have a power factor of 1.0. Even very large and very efficient motors do not very often exceed 0.95 power factor.

With energy saving device fitted	
volt	460
amp	68.8
kw	31
kva	32
pf	0.99

a) The power cannot be calculated but would probably be as high as without the energy saving device. In fact it would probably be higher due to the losses within the energy saver and the increase in i2R losses in the motor. The power quoted in this example appears to have been calculated on the basis of output current times output voltage times pf. (460 x 68.8 x 0.99 = 31.1KW). If we were to accept this calculation, then the power into the energy saver must be line volts times line current times pf, = 479.9 x 68.8 x 0.99 = 32.7KW. This would be what the consumer was paying for as the supply metering is on the input side of the energy saver, and the net result is that the consumer is paying for more!! If we continue on the assumption that the measurements and calculations are, in fact, valid, then the energy saver is dissipating 32.7KW - 31.1KW = 1.6KW and will therefore be operating at a very high temperature. I expect that if measurements were made in this installation, there would, in fact, be a net loss rather than a gain in overall efficiency.

b) Likewise, the KVA will be a little higher than before, 479 x 68.8 x 1.732 = 57KVA.

c) The energy saver should work to improve the power factor, not reduce it. If the power factor reduced, the energy saving device, (provided it was working correctly) would reduce the voltage further until the power factor rose again.

These results have definitely not been made with the correct instrumentation, or the instrumentation has not been used/ interpreted correctly. It is obvious that some of these figures are not measured results, but would appear to be incorrectly calculated. I suspect that perhaps the voltage and current readings could be true representations of the installation, but the KW, KVA and pf with and without the energy saver can not be correct.

A second quoted example is for a 10 ton roof top air conditioner.

Tests quoted were:

Without energy saving device	
volt	485
amp	31.2
kw	24.8
pf	0.95

The quoted kw would appear correct based on the quoted voltage, current and power factor.

With energy saving device fitted	
volt	430
amp	26.4
kw	17.8
pf	0.91

a) The quoted power is equal to the calculated value based on a calculation using the reduced output voltage. This could not be a measured value, as a measured value would certainly not reduce by this amount. As described earlier, the metering is not affected by the reduced output voltage.

b) The quoted power factor has dropped from 0.95 to 0.91. This is contrary to the basic operation of the device. The power factor should improve when the energy saver is used.

c) With a power factor of 0.95 initially, there would not be a drop in current with a falling voltage. As the majority of the KW load is shaft load, a drop in voltage will result in an increase in supply current. If we assumed that in this case we were using an inefficient motor at say 80% efficiency, then we would have a shaft load of 24.80 x 0.80 = 19.84 kw. The shaft load portion of the current at 485 volts would be 23.617 amps per phase. If the voltage was now reduced to the quoted 430 volts, then the shaft load KW remains constant and the shaft load current would rise to 19.84 / 430 / Å3 = 26.6 amps which is slightly above the quoted current at the reduced voltage. As there would still be magnetizing current, copper loss current and iron loss current, it would appear that these figures are also fictitious.

These are only a couple of randomly selected examples.

Another supplier quotes “in typical applications, levels of utilization are approximately 50% with power wastage estimated to be between 40% and 80% of the motor full load rating”. – “Unfortunately, motors have no way of intelligently adjusting the amount of electricity they draw in relation to the work they do.” The implication is that the motor is inherently very inefficient at less than full load, but this is not what the motor manufacturers show in their data sheets. This supplier also “delivers a speedy payback – normally less than two years”.???

5. PAY BACK PERIODS

In the right applications, with the right motors, there will be some energy saved. In many such situations, the energy saved would be increased by altering the operation of the machine to spend less time idling. To calculate the payback period, it is essential to have an accurate measurement of the actual energy (KW) being saved. When the energy saved is known and verified, then this can be multiplied by the cost of the energy per kilowatt hour to give a cost saving per hour. Dividing the savings per kilowatt hour into the installed cost of the energy saver will give the required number of operating hours to give a payback.

For example, a small punch press operated by a 1.1 KW motor, could save as much as 300 Watts per hour, depending on the design of the fitted motor. If the cost of energy is 14 cents per KWH, then at a 40 hour week operation this would amount to a cost saving of $1.68 per week. To achieve a pay back period of two years, this would require a maximum installed cost of $168.00. Prices quoted recently by one supplier would put the cost of the unit at $3,633.83, or a payback period of 43.2 years! or a return on investment of 2.3 percent per annum! With a larger motor, perhaps 22 KW operating a granulator which runs continuously, and spends 90% of its time unloaded, the potential savings could be as much as 1.1 KW per hour during the off load period, amounting to 40 x 1.1 x 0.9 = 39.6 KWH per week. At 14 cents per kWh, this would amount to a savings of $5.54 per week. To achieve a payback of two years, this would require a maximum installed cost of $554.40. A quoted price of $4919.07 would yield a payback period of 17.7 years, or a return on investment of 5.6%. A greater saving would be made by switching the machine off and only operating it on demand. Turning the machine OFF during its off load time could save 2.5 KW per hour which amounts to a saving of $12.60 per week or $630 per year, which is much higher than that achieved by using an energy saver.

In many industrial environments, the cost per KWH would be less than the 14 cents used in the equations, and therefore payback periods would be greater, or installed costs must be less than the examples above.

If we take a typical 75 Kw 2 pole motor, and operate it in its most inefficient state, (open shaft) then we could achieve a 1.5 KW saving. At 14 cents per KWh, this would amount to a saving of $420 per year if the motor runs for 40 hours per week. To achieve a payback of two years in this situation, the installed cost of the energy saver would need to be less than $840. In reality, with loads of this size connected, the energy cost would be lower, and the machine would not spend 100% time at idle, so the energy saved would be less and the payback period would be much longer. The cost of a unit to operate on a motor of this size would be a lot more expensive than this also. In this case using the figures quoted, the payback period would be 25.9 years.

CONCLUSIONS

There is no doubt that the basic technology of reducing the voltage on a motor which is operating at less than maximum efficiency can result in a reduction of the iron loss of the motor. In a case where the motor has a very high magnetizing current and it is operating at essentially open shaft conditions, there can be a reduction in copper loss also. In practice, with a partially loaded motor, a reduction in the voltage applied to the motor will reduce the iron loss, but the corresponding increase in the load current can cause an increase in copper loss that is greater than the reduction in the iron loss, resulting in a net increase in motor losses.

Worthwhile power savings are only achievable where the iron loss is an appreciable portion of the total power consumed by the motor, and where the amount of the iron loss is significant relative to the motor rating. This technology only achieves useful results on small, inefficient and predominantly single-phase motors.

Unfortunately, once again we have examples where a lack of knowledge about basic motor characteristics and a poor understanding of power metering on three-phase systems have resulted in extrapolations and estimations which totally misrepresent the achievable results from the application of this technology. Only energy that is being wasted can be saved. Large motors do have a much higher efficiency than small motors, and this basic fact seems to be missed in creating examples of potential energy savings. Proper tests would demonstrate that energy savings per kw motor rating are much higher for small motors than large, and the potential market for this technology is really confined to the small single-phase applications. I can find no evidence of a technological advancement which can result in increased energy savings over and above the energy wasted by the motor. According to current laws of physics, this would be considered an impossibility.

Worked examples based on energy costs, motor losses and quoted energy saver pricing yield payback periods in the 10 to 40 year range, nowhere near the quoted figures of less than two years! In many cases, the return on investment is well below standard bank interest rates. To borrow the money to purchase the equipment would be a loss situation. Putting the cash into a savings account would be a higher yielding investment than the purchase of some of these energy saving devices.

In summary, I would like to note the following points:

The basic concept of reducing the voltage on induction motors operating at less than full load, and thereby reducing the energy consumed, works provided that several constraints are applied.

a) The motor efficiency can only be improved when it has dropped considerably below the maximum efficiency for that motor.

b) As the maximum energy that can be saved is a portion of the iron loss, the best savings are going to be on motors with a very high iron loss. Typically, these will be small motors, operating above their design voltage, or below their design frequency.

c) Where payback periods are a consideration, the savings need to be related, not to the power consumed while the unit is running, but to the power saved relative to the cost of the unit, which is dependent on the motor rating.

d) Tests need to be carried out using rotating disk kWh meters, and care must be taken that the operating conditions are the same with and without the energy saver connected. Tests under open shaft conditions yield a high percentage saving, but the actual savings in kWh is indicative of the maximum dollar saving that can be achieved with that motor. As the load increases, the kWh savings will reduce, as will the percentage energy savings.

e) In many situations where energy savings can be made, greater energy savings can be achieved by either altering the operation of the machine to minimize the time operating at idle, or replacing the motor with a more efficient motor. This can yield an improved payback period relative to the use of an energy saving device.

f) Partially loaded motors fitted with energy saving devices can dissipate more energy than without the energy saving device.

g) Experience gained with this type of technology indicated that there was no significant improvement to be made on motors operating with a power factor greater than 0.4.

h) Experience has shown that the best results are on small single phase motors operating continuously and predominantly under no load conditions. Small motors operating at a voltage well above their design voltage (i.e. 440Volt motor operating on 485Volt) will exhibit a much higher iron loss and therefore achieve much increased savings.

i) Real payback periods of less than two years are rare, requiring a very good application, a very lossy motor and a very cheap energy saver.

SOLUTION TO HARMONICS, CAPACITOR, DE-TUNED CAPACITOR & FILTER BANK PRODUCTS

Courtesy ABB Inc.

THE HARMONIC PROBLEM...

Harmonic distortion and related problems in electrical power systems are becoming more and more prevalent in electrical distribution systems!!

PROBLEMS CREATED BY HARMONICS

- Excessive heating and failure of capacitors, capacitor fuses, transformers, motors, fluorescent lighting ballasts, etc.
- Nuisance tripping of circuit breaker or blown fuses
- Presence of the third harmonic & multiples of the third harmonic in neutral grounding systems may require the de-rating of neutral conductors
- Noise from harmonics that lead to erroneous operation of control system components
- Damage to sensitive electronic equipment
- Electronic communications interference

Any device with non-linear operating characteristics can produce harmonics in your power system. If you are currently using equipment that can cause harmonics or have experienced harmonic related problems, capacitor reactor or filter bank equipment may be the solution. The following is a discussion of harmonics; the characteristics of the problem; and a discussion of our solution.

ORIGINS OF HARMONIC DISTORTION

The ever increasing demand of industry and commerce for stability, adjust-ability and accuracy of control in electrical equipment led to the development of relatively low cost power diodes, thyristor, SCRs and other power semiconductors. Now used widely in rectifier circuits for UPS systems, static converters and AC & DC motor control, these modern devices replace the mercury arc rectifiers of earlier years and create new and challenging conditions for the power engineer of today.

Although solid state devices, such as the thyristor, have brought significant improvements in control designs and efficiency, they have the disadvantage of producing harmonic currents.

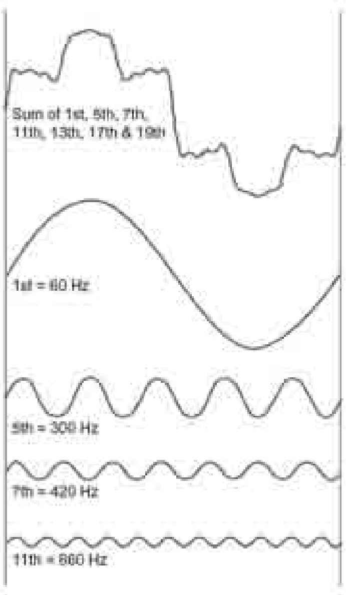
Harmonic currents can cause a disturbance on the supply network and adversely affect the operation of other electrical equipment including power factor correction capacitors.

We are concentrating our discussions on harmonic current sources associated with solid state power electronics, but there are actually many other sources of harmonic currents. These sources can be grouped into three main areas:

1. Power electronic equipment: Variable speed drives (AC VFDs, DC drives, PWM drives, etc.); UPS systems, rectifiers, switch mode power supplies, static converters, thyristor systems, diode bridges, SCR controlled induction furnaces and SCR controlled systems.
2. Arcing equipment: Arc furnaces, welders, lighting (mercury vapor, fluorescent)
3. Saturable devices: Transformers, motors, generators, etc. The harmonic amplitudes on these devices are usually insignificant compared to power electronic and arcing equipment, unless saturation occurs.

WAVEFORM

Harmonics are sinusoidal waves that are integral multiples of the fundamental 60 Hz waveform (i.e., 1st harmonic = 60 Hz; 5th harmonic = 300 Hz). All complex waveforms can be resolved into a series of sinusoidal waves of various frequencies, therefore any complex waveform is the sum of a number of odd or even harmonics of lesser or greater value. Harmonics are continuous (steady state) disturbances or distortions on the electrical network and are a completely different subject or problem from line spikes, surges, sags, impulses, etc., which are categorized as transient disturbances. Transient problems are usually solved by installing suppression or isolation devices such as surge capacitors, isolation transformers or MOVs These devices will help solve the transient problems but will not affect the mitigation of low order harmonics or solve harmonic resonance problems.



HARMONIC CONTENT

Thyristor and SCR converters are usually referred to by the number of DC current pulses they produce each cycle. The most commonly used are 6 pulse and 12 pulse.

There are many factors that can influence the harmonic content but typical harmonic currents, shown as a percentage of the fundamental current, are given in the following table. Other harmonics will always be present to some degree, but for practical reasons, they have been ignored.

Order of harmonic	Typical percentage of harmonic current	
	6 Pulse	12 Pulse
1	100	100
5	20	–
7	14	–
11	9	9
13	8	8
17	6	–
19	5	–
23	4	4
25	4	4

HARMONIC OVERLOADING OF CAPACITORS

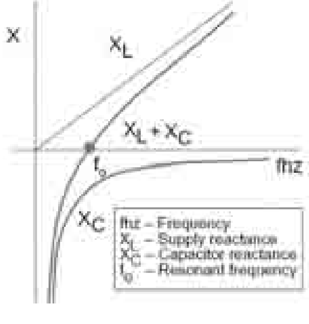
The impedance of a circuit dictates the current flow in that circuit. As the supply impedance is generally considered to be inductive, the network impedance increases with frequency while the impedance of a capacitor decreases. This causes a greater proportion of the currents circulating at frequencies above the fundamental supply frequency to be absorbed by the capacitor, and all equipment associated with the capacitor.

In certain circumstances, harmonic currents can exceed the value of the fundamental (60 Hz) capacitor current. These harmonic problems can also cause an increased voltage across the dielectric of the capacitor which could exceed the maximum voltage rating of the capacitor, resulting in premature capacitor failure.

HARMONIC RESONANCE

The circuit or selective resonant frequency is reached when the capacitor reactance and the supply reactance are equal.

Whenever power factor correction capacitors are applied to a distribution network which combines capacitance and inductance, there will always be a frequency at which the capacitors are in parallel resonance with the supply. If this condition occurs on, or close to, one of the harmonics generated by solid state control equipment, then large harmonic currents can circulate between the supply network and the capacitor equipment. These currents are limited only by the damping resistance in the circuit. Such currents will add to the harmonic voltage disturbance in the network causing an increased voltage distortion. This results in a higher voltage across the capacitor and excessive current through all capacitor components. Resonance can occur on any frequency but, in general, the resonance we are concerned with is on, or close to, the 5th, 7th, 11th and 13th harmonics for 6 pulse systems.



AVOIDING RESONANCE

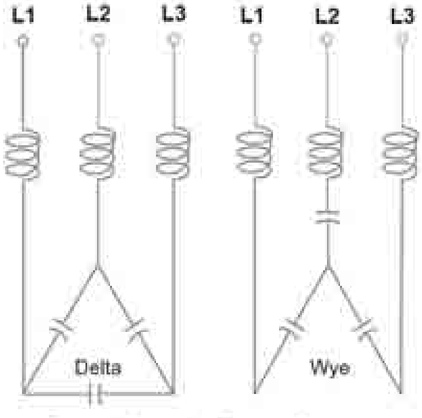
There are a number of ways to avoid resonance when installing capacitors. In larger systems it may be possible to install them in a part of the system that will not result in a parallel resonance with the supply. Varying the kvar output rating of the capacitor bank will alter the resonant frequency. With capacitor switching there will be a different resonant frequency for each step.

Changing the number of switching steps may avoid resonance at each step of switching.

OVERCOMING RESONANCE

If resonance cannot be avoided, an alternative solution is required. A reactor must be connected in series with each capacitor such that the capacitor/reactor combination is inductive at the critical frequencies but capacitive at the fundamental frequency. To achieve this, the capacitor and series connected reactor must have a tuning frequency below the lowest critical order of harmonic, which is usually the 5th. This means the tuning frequency is in the range of 175 Hz to 270 Hz, although the actual frequency will depend upon the magnitude and order of the harmonic currents present.

The addition of a reactor in the capacitor circuit increases the fundamental voltage across the capacitor. Therefore, care should be taken when adding reactors to existing capacitors.

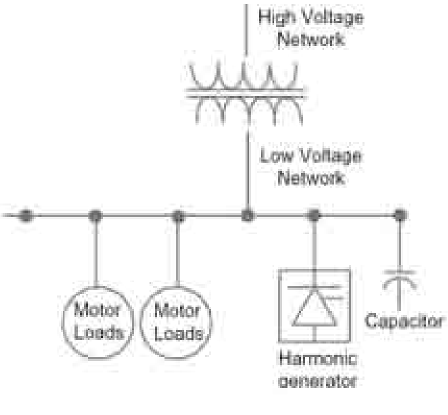


Detuned Capacitor/Reactor Systems

REDUCTION OF HARMONIC DISTORTION

Harmonic currents can be significantly reduced in an electrical system by using a harmonic filter.

In its basic form, a filter consists of a capacitor connected in series with a reactor tuned to a specific harmonic frequency. In theory, the impedance of the filter is zero at the tuning frequency; therefore, the harmonic current is absorbed by the filter. This, together with the natural resistance of the circuit, means that only a small level of harmonic current will flow in the network.



TYPES OF FILTERS

The effectiveness of any filter design depends on the reactive output of the filter, tuning accuracy and the impedance of the network at the point of connection.

Harmonics below the filter tuning frequency will be amplified. The filter design is important to ensure that distortion is not amplified to unacceptable levels. Where there are several harmonics present, a filter may reduce some harmonics while increasing others. A filter for the 7th harmonic creates a parallel resonance in the vicinity of the 5th harmonic with magnification of the existing 5th harmonic; therefore, a 7th harmonic filter requires a 5th harmonic filter. Consequently, it is often necessary to use a multiple filter design where each filter is tuned to a different frequency. Experience is extremely important in the design of such filters to ensure:

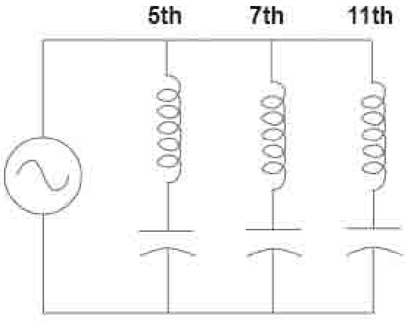
a) the most efficient and cost effective solution is selected;
b) no adverse interaction between the system and the filter.

LOAD ALTERATION

Whenever load expansion is considered, the network is likely to change and existing filter equipment should be evaluated in conjunction with the new load condition. It is not recommended to have two or more filters tuned to the same frequency connected on the same distribution system. Slight tuning differences may cause one filter to take a much larger share of the harmonic distortion. Or, it may cause amplification of the harmonic order which the equipment has been designed to reduce. When there is a need to vary the power factor correction component of a harmonic filter, careful consideration of all load parameters is necessary.

HARMONIC ANALYSIS

The first step in solving harmonic related problems is to perform an analysis to determine the specific needs of your electrical distribution system. To determine capacitor and filter requirements, it is necessary to establish the impedance of the supply network and the value of each harmonic current. Capacitor, reactor and filter bank equipment are then specified under very detailed and stringent computer analysis to meet your needs.



Shunt Filters

AC DRIVE MOTORS – INFLUENCE OF DRIVE ON ACOUSTICAL NOISE

ABB Industrial Systems, Inc.

1. INTRODUCTION

DRIVE CONTRIBUTION TO ACOUSTICAL NOISE

The output voltage waveform of an adjustable frequency drive is not a sine wave but a series of square wave voltage pulses that result in a reasonable approximation of a sine wave current. Although there is an extensive history of successful use of standard motors on this waveform, the possible effects of the waveform should be carefully considered. One effect is the generation of acoustical noise in addition to the noise ordinarily produced by an AC motor. This technical guide explains this phenomenon and gives recommendations on minimizing noise when using ABB adjustable frequency drives.

USING THIS GUIDE

This guide has been designed to provide an understanding of the characteristics of adjustable frequency drives as related to acoustical noise produced by the motors used with them. The background discussion leads to recommendations for selecting and applying drives and motors to limit motor noise to an acceptable level.

2. PWM ADJUSTABLE FREQUENCY DRIVES

ABB adjustable frequency drives and most other AC drives that are available today are Pulse Width Modulated (PWM) drives. Figure 1 illustrates the basic principles of PWM drives. The rectifier converts input line power, which has a nominally fixed voltage and frequency to fixed voltage DC power. A filter then reduces the ripple voltage resulting from the rectification of the AC line. The inverter changes the fixed voltage DC power to ac output power of an adjustable voltage and frequency.

The output waveform consists of a series of rectangular voltage pulses with a fixed height and adjustable width. Adjusting the overall pattern of positive vs. negative pulses establishes the output frequency. The width of the individual pulses is varied so that the effective voltage is regulated in proportion to the frequency. Proper motor performance requires an essentially constant ratio of output voltage to output frequency (volts per hertz or V/Hz).

The characteristics and effects of adjustable frequency waveforms are often analyzed using Fourier analysis. The basic principle of Fourier analysis is that any periodic waveform is equivalent to the sum of an infinite series of variable amplitude sine waves with frequencies which are integral multiples of the fundamental frequency. These sine wave component parts are called harmonics.

One cycle of the output waveform at a given output voltage can be made from many narrow pulses or fewer wider pulses. To generate a waveform containing more pulses, the switching devices in the inverter must switch more often. The rate at which the switches operate is called the switching frequency or carrier frequency.

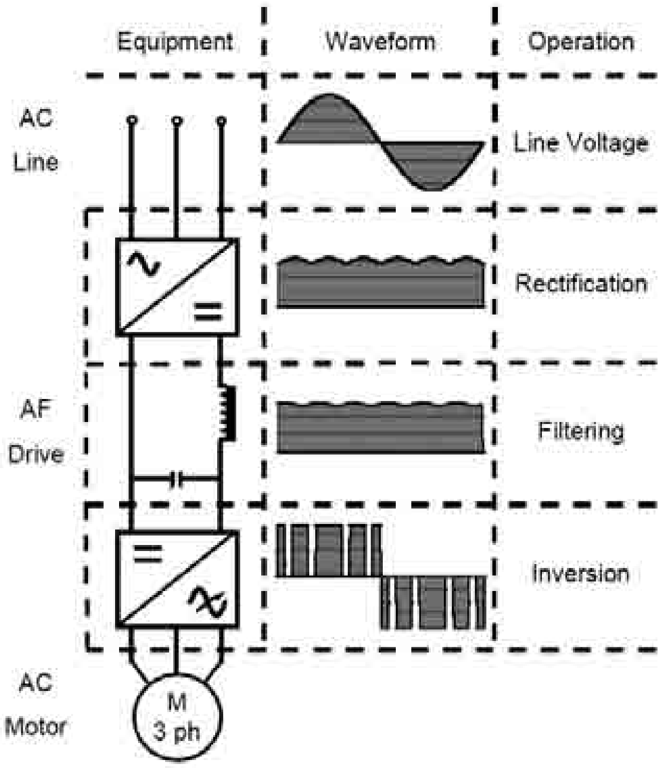


Figure 1. Principles of Operation for ABB Adjustable Frequency Drives

3. ACOUSTICAL NOISE PRODUCED BY MOTORS

Regardless of power source, all AC motors produce a significant level of acoustical noise during normal operation. The predominant sound is the sound produced by the air that is forced through the motor or over its surface to cool the motor. In addition, noise results from the small amount of vibration caused by the normal electromagnetic and mechanical forces inside the motor.

The harmonic voltages that are present in the PWM waveform produce harmonic currents in the stator of the motor. The magnetic fields produced by the harmonic currents can cause vibrations in the mechanical structure of the motor stator. This effect is more significant if the frequency of the harmonic currents corresponds to the mechanical resonant frequency of some part of the motor. The most noticeable effect of these vibrations is the resulting sound, which has a pitch equivalent to the harmonic frequency.

The primary concern is the effect of noise on the comfort and safety of personnel. If the sound level in a work area is near the upper limit for personnel safety, the effect of adjustable frequency power on a motor might push the sound level over the limit, but this is not a common problem. A more common problem is the disturbance of a relatively quiet office area by a minor change in background noise due to the sound produced by an adjustable frequency driven motor. There may be some concern that the motor may be damaged by the vibrations producing the sound. This should not be a concern. These vibrations occur at frequencies where only a tiny vibration amplitude can produce a noticeable sound. There have been a few reports of mechanical damage to winding insulation due to vibration of winding coils that were not well secured, but such problems have been very rare.

4. RECOMMENDATIONS

If, when operating on 60 Hz sine wave power, the acoustical noise produced by the motor is at least 3 dB below the maximum acceptable level, some combination of the following measures will usually limit the noise to the acceptable level when the motor is connected to an ABB adjustable frequency drive. These measures are presented in order of usual preference.

Every motor reacts differently with respect to acoustical noise produced by a particular waveform. Two motors of the same design and rating from the same manufacturer have been known to produce significantly different noise levels under identical operating conditions due to subtle variations in motor manufacturing. Therefore, it is not possible to accurately predict noise level for any given motor.

USE GOOD QUALITY, HIGH EFFICIENCY MOTORS

Motors that are well designed and constructed are generally less susceptible to the effects of PWM waveforms. High efficiency motors are designed to operate at a lower magnetic flux density, resulting in quieter operation.

OPERATE AT REDUCED V/HZ

Reduced V/Hz operation can be employed in variable torque applications. These are applications where the required torque is proportional to the square of speed such as centrifugal pumps, fans or centrifugal compressors. By reducing the V/Hz at lower speeds where less torque is required, the motor is allowed to run at a reduced magnetic flux density resulting in quieter operation.

OPERATE AT THE OPTIMUM SWITCHING FREQUENCY

There are three ways in which adjusting the switching frequency may reduce the level of sound produced by the motor.

1) If the switching frequency or some harmonic of the switching frequency corresponds to a mechanical resonant frequency of the motor, it may be possible to reduce the noise level by raising or lowering the switching frequency to avoid the resonant point.
2) As the frequency of sound increases above 2000 Hz, more sound power is required to produce a given level of loudness as sensed by the human ear or by a sound level meter that is calibrated in dBA. Therefore, increasing the switching frequency, and thus the sound produced by the motor, may reduce the level of sound perceived.
3) Because the motor is an inductive load, it represents a higher impedance for harmonic voltages at higher frequencies. As a result, harmonic currents are reduced by raising the switching frequency. Reducing harmonic currents usually also reduces the noise level.

Although increasing the switching frequency usually reduces the noise produced by the motor, increasing the switching frequency also has a disadvantage. Every time a switching device switches on or off, power is lost in the process. When the switching frequency is increased, the switching devices are switched more often causing an increase in power losses. Increased power losses mean increased operating temperature and reduced efficiency.

Caution: Before increasing the switching frequency above the factory setting, consult the instruction manual and check with ABB to insure that, based on the ambient temperature and output currents present, safe operating limits will not be exceeded.

To minimize operating frequency and maximize efficiency, it is best to set the switching frequency at the lowest setting at which the sound level is acceptable.

This optimal switching frequency adjustment must be performed under actual service conditions for each individual motor. Note: Some models may not have a switching frequency adjustment.

USE THE CRITICAL FREQUENCY AVOIDANCE ADJUSTMENT

If the motor produces unacceptable noise only at a few specific operating speeds, the "Critical Frequency Avoidance" adjustments can possibly be set to prevent the drive from operating at specific speeds where problems are observed. In many applications, the drive can be "locked out" of a few narrow bands of the operating speed range without significantly limiting the overall process performance.

5 SUMMARY

This technical guide has described the influence of adjustable frequency operation on the sound produced by AC motors and recommended measures to limit the noise to an acceptable level. Following are some important points to remember:

- Regardless of power source, all AC motors produce a significant level of acoustical noise during normal operation.
- The harmonic content of the PWM drive output waveform causes additional noise at a pitch that is related to the harmonic frequency.
- In some installations, a motor may produce an objectionable level or frequency of noise when operating on PWM drive power.
- It is not possible to accurately predict the total noise level for any given motor.
- It is usually possible to limit the noise to an acceptable level by applying one or more of the following measures:
- Use a good quality motor of high efficiency design.
- Use reduced V/Hz operation in variable torque applications.
- Operate at the optimum switching frequency.
- Use the critical frequency avoidance adjustment.

BUYING AN ENERGY-EFFICIENT ELECTRIC MOTOR

U.S. Department of Energy

Efficiency is an important factor to consider when buying or rewinding an electric motor. This fact sheet shows you how to obtain the most efficient motor at the lowest price and avoid common problems. It answers the following frequently asked questions:

1. Why is improving motor efficiency important?
2. What is an energy-efficient motor?
3. What efficiency values should I use when comparing motors?
4. When should I consider buying an energy-efficient motor?
5. When is an energy-efficient motor cost effective?
6. Should I rewind a failed motor?
7. What design factors should I consider when choosing a new motor?
8. How should I begin a motor efficiency improvement program?
9. How can I obtain motor prices and efficiency values?
10. Where can I find additional information?

1. WHY IS IMPROVING MOTOR EFFICIENCY IMPORTANT?

Over half of all electrical energy consumed in the United States is used by electric motors. Improving the efficiency of electric motors and the equipment they drive can save energy, reduce operating costs, and improve the nation's productivity.

Energy efficiency should be a major consideration when you purchase or rewind a motor.

The annual energy cost of running a motor is usually many times greater than its initial purchase price. For example, even at the relatively low energy rate of $0.04/kWh, a typical 20-horsepower (hp) continuously running motor uses almost $6,000 worth of electricity annually, about six times its initial purchase price.

2. WHAT IS AN ENERGY-EFFICIENT MOTOR?

Motor efficiency is the ratio of mechanical power output to the electrical power input, usually expressed as a percentage. Considerable variation exists between the performance of standard and energy-efficient motors (see Figure 1). Improved design, materials, and manufacturing techniques enable energy-efficient motors to accomplish more work per unit of electricity consumed.

Energy-efficient motors offer other benefits. Because they are constructed with improved manufacturing techniques and superior materials, energy-efficient motors usually have higher service factors, longer insulation and bearing lives, lower waste heat output, and less vibration, all of which increase reliability. Most motor manufacturers offer longer warranties for their most efficient models.

To be considered energy efficient, a motor's performance must equal or exceed the nominal full-load efficiency values provided by the National Electrical Manufacturers Association (NEMA) in publication MG 1. Specific full-load nominal efficiency values are provided for each horsepower, enclosure type, and speed combination.

A motor's performance must equal or exceed the efficiency levels given in Table 1 of this fact sheet (reprinted from Table 12-10 of NEMA MG-1-1993, Rev. 1) for it to be classified as "energy efficient."

The Energy Policy Act of 1992 (EPACT) requires that most general purpose motors manufactured for sale in the United States after October 24, 1997 meet new minimum efficiency standards. These standards are identical to the shaded area of Table 1. The Act applies to 1- through 200-hp general-purpose, T-frame, single-speed, foot-mounted, continuous-rated, polyphase, squirrel-cage, induction motors conforming to NEMA designs A and B. Covered motors are designed to operate with 230 or 460 volt power supplies, have open or "closed" (totally enclosed) enclosures, and operate at speeds of 1200, 1800, or 3600 rpm.

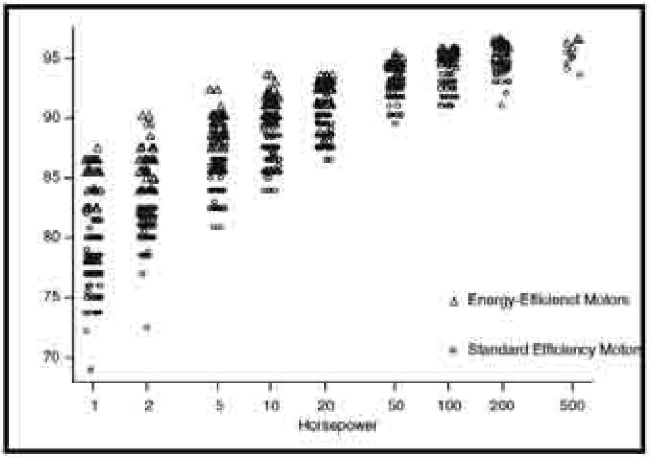


Figure 1. Standard and Energy-Efficient Motor Performances

3. WHAT EFFICIENCY VALUES SHOULD I USE WHEN COMPARING MOTORS?

When comparing motor efficiencies, be sure to use a consistent measure of efficiency. Nominal efficiency is best. Nominal efficiency is an average value obtained through standardized testing of a population of motors.

Minimum guaranteed efficiency, which is based on nominal efficiency, is slightly lower to take into account typical population variations. Minimum guaranteed efficiency is also less accurate, because the value is rounded. Other efficiency ratings, including apparent and calculated, should not be used.

In the United States, the recognized motor efficiency testing protocol is the Institute of Electrical and Electronics Engineers (IEEE) 112 Method B, which uses a dynamometer to measure motor output under load.

Different testing methods yielding significantly different results are used in other countries. The NEMA nameplate labeling system for design A and B motors in the 1- to 500-hp range uses bands of efficiency values based on IEEE 112 testing.

4. WHEN SHOULD I CONSIDER BUYING AN ENERGY-EFFICIENT MOTOR?

Energy-efficient motors should be considered in the following circumstances:

- For all new installations
- When purchasing equipment packages, such as compressors, HVAC systems, and pumps
- When major modifications are made to facilities or processes
- Instead of rewinding older, standard efficiency units
- To replace oversized and under loaded motors
- As part of a preventive maintenance or energy conservation program.

The cost effectiveness of an energy-efficient motor in a specific situation depends on several factors, including motor price, efficiency rating, annual hours of use, energy rates, costs of installation and downtime, your firm's payback criteria, and the availability of utility rebates. Check with your utility to determine whether it can fund a portion of your motor replacement costs through its energy conservation programs. Question 5 addresses methods for evaluating the cost effectiveness of energy-efficient motors.

Table 1
NEMA Threshold Full-Load Nominal Efficiency Values for Energy-Efficient Motors (from NEMA MG1 Table 12-10)[1]

Open Motors						Enclosed Motors				
hp	3600	1800	1200	900		hp	3600	1800	1200	900
1	—	82.5	80.0	74.0		1	75.5	82.5	80.0	74.0
1.5	82.5	84.0	84.0	75.5		1.5	82.5	84.0	85.5	77.0
2	84.0	84.0	85.5	85.5		2	84.0	84.0	86.5	82.5
3	84.0	86.5	86.5	86.5		3	85.5	87.5	87.5	84.0
5	85.5	87.5	87.5	87.5		5	87.5	87.5	87.5	85.5
7.5	87.5	88.5	88.5	88.5		7.5	88.5	89.5	89.5	85.5
10	88.5	89.5	90.2	89.5		10	89.5	89.5	89.5	88.5
15	89.5	91.0	90.2	89.5		15	90.2	91.0	90.2	88.5
20	90.2	91.0	91.0	90.2		20	90.2	91.0	90.2	89.5
25	91.0	91.7	91.7	90.2		25	91.0	92.4	91.7	89.5
30	91.0	92.4	92.4	91.0		30	91.0	92.4	91.7	91.0
40	91.7	93.0	93.0	91.0		40	91.7	93.0	91.7	91.0
50	92.4	93.0	93.0	91.7		50	92.4	93.0	93.0	91.7
60	93.0	93.6	93.6	92.4		60	93.0	93.6	93.0	91.7
75	93.0	94.1	93.6	93.6		75	93.0	94.1	93.6	93.0
100	93.0	94.1	94.1	93.6		100	93.6	94.5	93.6	93.0
125	93.6	94.5	94.1	93.6		125	94.5	94.5	94.1	93.6
150	93.6	95.0	94.5	93.6		150	94.5	95.0	94.1	93.6
200	94.5	95.0	94.5	93.6		200	95.0	95.0	95.0	94.1
250	94.5	95.4	95.4	94.5		250	95.4	95.0	95.0	94.5
300	95.0	95.4	95.4	—		300	95.4	95.4	95.0	—
350	95.0	95.4	95.4	—		350	95.4	95.4	95.0	—
400	95.4	95.4	—	—		400	95.4	95.4	—	—
450	95.8	95.8	—	—		450	95.4	95.4	—	—
500	95.8	95.8	—	—		500	95.4	95.8	—	—

[1] The shaded area indicates motor classes covered by the efficiency standards contained within the Energy Policy Act of 1992.

5. WHEN IS AN ENERGY-EFFICIENT MOTOR COST EFFECTIVE?

The extra cost of an energy-efficient motor is often quickly repaid in energy savings. As illustrated in Table 2, each point of improved motor efficiency can save significant amounts of money each year. In typical industrial applications, energy-efficient motors are cost effective when they operate more than 4000 hours a year, given a 2-year simple payback criterion. For example, with an energy cost of \$0.04/kWh, a single point of efficiency gain for a continuously operating 50-hp motor with a 75% load factor saves 4079 kWh, or \$163 annually. Thus, an energy-efficient motor that offers four points of efficiency gain can cost up to \$1,304 more than a standard model and still meet a 2-year simple payback criterion. A utility rebate program would further enhance the benefits of an energy-efficient motor.

Whenever possible, obtain actual price quotes from motor distributors to calculate simple paybacks. Motors rarely sell at full list price. You can typically obtain a 20% to 60% discount from vendors, with specific prices depending on the distributor's pricing policies, the number and type of motors you buy, and fluctuations in the motor market.

Table 2
Annual Value of a One-Point Efficiency Gain (Based on \$0.04/kWh, 8000 Hours of Use, Full Load)

Horsepower	Annual Savings
5	\$17
10	\$32
20	\$61
50	\$142
100	\$278
200	\$537

COMPARISON

The following three techniques can help you determine whether an energy efficient motor is cost effective:

1. Use the MotorMaster or Windows-based MotorMaster+ software program to calculate the dollar savings and simple payback from using a more efficient motor, taking into account motor size, price, efficiency, and annual hours of use, load factor, electricity costs, and utility rebates. MotorMaster can be used to analyze a new motor purchase, rewind of a failed motor, or replacement of a working motor. This program is described in further detail in the answer to Question 9.
2. Use the following formulas to calculate the annual energy savings and simple payback from selecting a more efficient motor. Simple payback is defined as the time required for the savings from an investment to equal the initial or incremental cost.

Annual Energy Savings

$$\text{Savings} = \text{hp} \times L \times 0.746 \times \text{hr} \times C \times \left[\frac{100}{E_{std}} - \frac{100}{E_{ee}}\right]$$

E Savings = Expected annual dollar savings
hp = Motor rated horsepower
L = Load factor (percentage of full load/100)
hr = Annual operating hours
C = Average energy costs (\$/kWh)
Estd = Standard motor efficiency rating, %
Eee = Energy-efficient motor efficiency rating, %
0.746 = Conversion from horsepower to kW units

Simple Payback

For a new motor purchase, the simple payback is the price premium minus any utility rebate for energy-efficient motors, divided by the annual dollar savings:

$$\underset{\text{(years)}}{\text{Simple payback}} = \frac{\text{Price premium} - \text{Utility rebate}}{\text{Annual dollar savings}}$$

When calculating the simple payback for replacing an operating motor, you must include the full purchase price of the motor plus any installation costs:

$$\underset{\text{(years)}}{\text{Simple payback}} = \frac{\text{Motor price} + \text{Installation charge} - \text{Utility rebate}}{\text{Annual dollar savings}}$$

3. Use Table 3 to determine whether a new energy-efficient motor will meet common payback criteria. Table 3, which is based on typical motor efficiencies and prices, indicates the minimum number of hours a year a motor must be used at various energy prices in order to obtain a 2-, 3-, and 4-year simple payback. This technique is less accurate than a more detailed analysis. The calculation of values for Table 3 assumes that an energy-efficient motor has a 15% to 25% price premium with no utility rebate, and it ignores other benefits of energy-efficient motors. A lower price premium, a rebate program, or reliability benefits make energy-efficient motors even more cost effective.

Choose a new energy-efficient 1- to 100-hp motor if it will be used more than the indicated number of hours each year.

6. SHOULD I REWIND A FAILED MOTOR?

Although failed motors can usually be rewound, it is often worthwhile to replace a damaged motor with a new energy-efficient model to save energy and improve reliability. When calculating operating costs for rewound motors, deduct one efficiency point for motors exceeding 40 hp and two points for smaller motors. Have motors rewound only at reliable repair shops that use low temperature (under 700°F) bake-out ovens, high quality materials, and a quality assurance program based on EASA-Q or ISO-9000. Ask the repair shop to conduct a core loss or loop test as part of their rewind procedures.

Select a new energy-efficient motor under any of the following conditions:

- The motor is less than 40 hp.
- An energy-efficient motor is recommended according to Table 3.
- The cost of the rewind exceeds 65% of the price of a new motor.
- The motor was rewound before 1980.

Table 3
Minimum Hours per Year of Motor Use that Meet Various Simple Payback Criteria

(Choose a new energy-efficient 1- to 100-hp NEMA design A or B motor if it will be used more than the indicated number of hours each year.)

simple payback period	Average Energy Price (Cents/kWh)			
	2	4	6	8
2 years	8760	6000	4000	3000
3 years	7000	4000	3000	2000
4 years	6000	3000	2000	1500

7. WHAT DESIGN FACTORS SHOULD I CONSIDER WHEN CHOOSING A NEW MOTOR?

Motor Size. Size motors for efficiency. Motors should be sized to operate with a load factor between 65% and 100%. The common practice of over sizing results in less efficient motor operation. For example, a motor operating at a 35% load is less efficient than a smaller motor that is matched to the same load (see Figure 2).

Of course, some situations may require over sizing for peak loads, but in such cases alternative strategies should be considered, such as a correctly sized motor backed up with a pony motor.

Operating Speed. Select replacement energy-efficient motors with a comparable full-load speed for centrifugal load applications (pumps and fans). Induction motors have an operating speed that is slightly lower than their rated synchronous speed. For example, a motor with a synchronous speed of 1800 rpm will typically operate under full load at about 1750 rpm. Operating speed (full-load rpm) is stamped on motor nameplates.

The difference between the synchronous speed and the operating speed is called slip. Slip varies with load and the particular motor model.

Every pump and fan has a design speed. Centrifugal pump and fan loads are extremely sensitive to speed variations; an increase of just 5 rpm can significantly affect the pump or fan operation, leading to increased flow, reduced efficiency, and increased energy consumption. Whenever a pump or fan motor is replaced, be sure to select a model with a full-load rpm rating equal to or less than that of the motor being replaced.

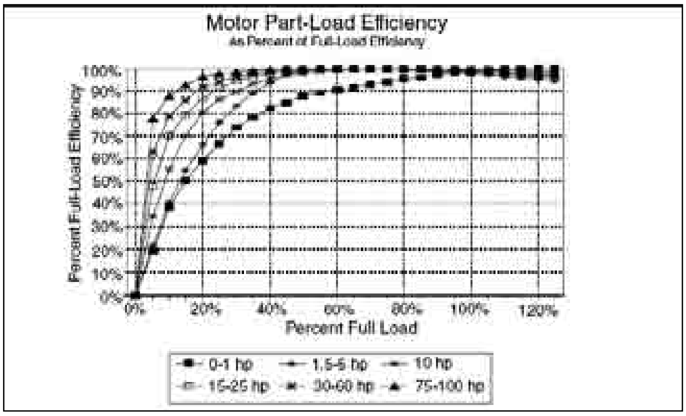


Figure 2. Part-Load Motor Efficiency Range

Inrush Current. Avoid overloading circuits. Energy-efficient motors feature low electrical resistance and thus exhibit higher inrush currents than standard models. The inrush current duration is too short to trip thermal protection devices, but energy-efficient motors equipped with magnetic circuit protectors can sometimes experience nuisance starting trips.

8. HOW SHOULD I BEGIN A MOTOR EFFICIENCY IMPROVEMENT PROGRAM?

Survey your motors. Gather nameplate information and obtain field measurements (voltage, amperage, power factor, operating speed) under typical operating conditions. Initially focus on motors that exceed minimum size and operating duration criteria. Typical selection criteria include:

- Three-phase NEMA design B motor
- Non-specialty motor
- 10 to 600 hp
- At least 2000 hours per year of operation
- Constant load (not intermittent, cyclic, or fluctuating)
- Older or rewound standard efficiency motors
- Easy access
- Readable nameplate.

Conduct motor replacement analyses (with MotorMaster+) and divide your motors into the following three categories:

Replace Immediately – Motors Offering Rapid Payback through Energy Savings, Improved Reliability, or Utility Rebates. These include motors that run continuously (typically 8000 or more hours a year), are currently inefficient (including oversized motors), must be reliable, or are covered by attractive utility rebate programs. Order an efficient replacement motor soon and install it at the next available opportunity, such as during a scheduled downtime.

Replace at Time of Failure – Motors with Intermediate Payback. When these motors fail, you will want to replace them with an energy-efficient model. Now is the time to contact motor dealers to review the efficiency and prices of available motors. After identifying the most cost-effective replacement model, you must decide whether to purchase it and keep it on hand as a spare, or wait to purchase it until the existing motor fails. This choice depends on how quickly an energy-efficient motor can be obtained through suppliers, how quickly a failed motor must be replaced, and how many motors of the same size and type are used in your facility.

Leave Present Situation as is – Motors with Extended Payback. These motors are already reasonably efficient or are used less than 2000 hours each year. They can be rewound or replaced with a similar motor.

Motors and drive systems have a long useful life. The cost of running a motor may increase significantly in the future. Energy efficiency improvements that are not justified today may become worthwhile in a few years, so periodically reevaluate paybacks and reliability. It is also important to operate your motor efficiently. Keep the following two issues in mind:

Power Quality. Address power quality problems. To improve motor reliability and efficiency, it is important to maintain the correct voltage and phase balance, identify and eliminate current leaks, and prevent harmonics in the electrical supply. It is a good idea to have an electrical engineer review the electrical system periodically, especially before installing a new motor or after making changes to the system and its loads. Consult the manufacturer before installing any motor under conditions of poor power quality.

Periodic Maintenance. It is important to maintain motors according to manufacturers' instructions. Although energy-efficient motors with higher temperature-rated insulation may be able to handle higher temperatures and other abuse, there is no reason to reduce maintenance. Motors should have good ventilation and be periodically inspected for increased vibration or power supply problems.

9. HOW CAN I OBTAIN MOTOR PRICES AND EFFICIENCY VALUES?

MotorMaster+ software helps you choose the most efficient and cost-effective motor for your application. The MotorMaster+ database contains performance information and list prices for over 13,800 NEMA design B motors, ranging from 1 to 600 hp. Full- and part-load efficiencies, power factor, full-load rpm, voltage, frame size, service factor, and list price are available for each model. You specify the horsepower, speed, enclosure type, and operating voltage to obtain a list of available models ranked in order of descending full-load efficiency values.

MotorMaster+ calculates the energy consumption of a motor in a specific application, taking into account efficiency ratings, energy costs, hours of use, and load factor. It calculates the load and annual energy efficiency of the existing motor (based upon field measurements), demand and dollar savings, and simple payback period due to selecting a more efficient motor model. Utility rebate values can be incorporated in payback or life-cycle cost calculations.

MotorMaster+ can be obtained by contacting the Motor Challenge Information Clearinghouse at (800) 862-2086. You will receive disks, telephone support, and users' manual. MotorMaster+ requires an IBM-compatible computer with the capacity to run Windows 3.1, Windows for Workgroups, or Windows 95. This means a 386 or higher microprocessor, at least 8 MB of memory, and a hard disk with at least 15 MB of free disk space.

10. WHERE CAN I FIND ADDITIONAL INFORMATION?

The Motor Challenge Program, Washington State University Cooperative Extension, and the Bonneville Power Administration have prepared a number of publications on motor efficiency topics. Examples include: The Motor Challenge Sourcebook, An Energy Management Guide for Motor-Driven Systems, the Energy Efficient Electric Motor Selection Handbook, the Adjustable Speed Drive Applications Guidebook, Optimizing Your Motor Drive System, Determining Electric Motor Load Factor, and Reducing Power Factor Cost. Call the Motor Challenge Clearinghouse for details about ordering these or other motor-related documents.

ABOUT MOTOR CHALLENGE

Motor Challenge is a partnership program between the U.S. Department of Energy and the nation's industries. The program is committed to increasing the use of industrial energy-efficient electric motor systems and related technologies. The program is wholly funded by the U.S. Department of Energy and is dedicated to helping industry increase its competitive edge, while conserving the nation's energy resources and enhancing environmental quality.

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MONITORING VARIABLE FREQUENCY DRIVES (VFD)

By William D. Walden, Ohio Semitronics, Inc.

Most modern variable frequency drives operate by converting a three-phase voltage source to DC and use insulated gate bipolar transistors (IGBTs) to switch the DC voltage on and off at typically 3000 to 4000 hertz. Varying the duration or width of the individual pulses [pulse width modulation (PWM)] controls the effective voltage. To help "shape" the synthesized sine wave, intermixed positive and negative pulses are used at lower displacement of the synthesized sine wave.

MEASURING THE VOLTAGE

True RMS measuring transducers and meters will read higher than the user expects. The true RMS measuring transducer and/or meter are registering the correct RMS value of the applied voltage.

True RMS voltage-measuring transducers manufactured by Ohio Semitronics, Inc. and most true RMS measuring meters are fast enough to measure the RMS value of the PWM voltage. The RMS value of the pulse train is higher than the RMS value of the synthesized sine wave.

Customers ask, "How can I read the correct value of the applied voltage?" Well, they are reading the correct value.

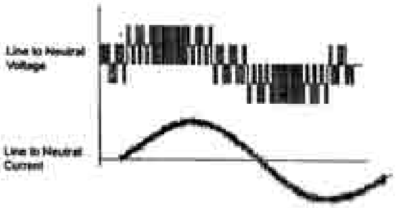


Figure 1. Voltage and current wave shapes produced by a typical variable frequency drive.

$$V_{eff} := \sqrt{\left(\frac{1}{T}\right) \cdot \int_{0}^{T} (f(v))^2 dt}$$

Figure 2. RMS Calculation of the voltage

f(v) is the function of the voltage for the RMS calculation. In the case of the VFD, the voltage function consists of a series of voltage pulses of varying width that are both positive and negative. By squaring the pulses ([f(v)]2), all pulses (including negative swinging pulses interspersed with the positive swinging pulses and the positive swinging pulses interspersed with the negative swing pulses) contribute to the RMS value. As a result, the true RMS or effective voltage produced is higher than expected compared to the synthesized sine wave voltage envelope.

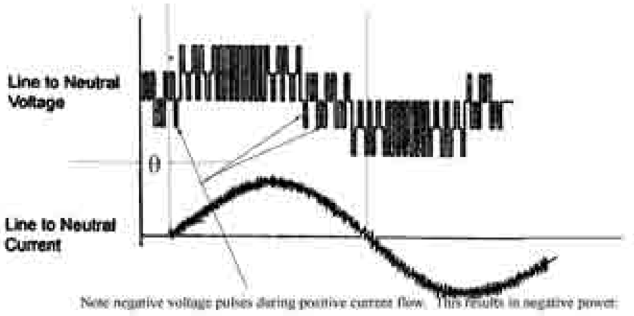
MEASURING THE CURRENT

Because a motor load is inductive, it filters out the high frequency component from the VFD and the current is observed as a sine wave with ripple. A true RMS measuring meter or transducer measures the effective current used by the motor load.

MEASURING THE POWER

Because the synthesized voltage sine wave from the VFD may vary from near DC to some nominal AC frequency such as 66 hertz, power measurement devices must have a response from DC to the maximum expected synthesized frequency and must respond fast enough to capture the pulse width modulation frequency.

A properly designed power transducer will multiply the individual voltage pulses by the current and average the product over a sufficient time period to give a relatively smooth output.



Note negative voltage pulses during positive current flow. This results in negative power.

Figure 3

Figure 3 is figure 1 again with some comments. θ is the angle by which the current lags the voltage – the power factor angle. This is indicative of an inductive load. Note the negative voltage pulses occurring while the current is positive.This results in negative power flow. Likewise, note the positive voltage pulses occurring while the current is negative. This too results in negative power.

The power measured by the variable frequency power transducer reflects the power consumed by the motor developing shaft power, resistive losses that are normal with a motor, and the additional resistive losses as a result of the pulse width modulated voltage.

As a result of the latter, an induction motor operating from a VFD will run a little hotter. To correct for this, some motor manufacturers specify using a reactor between the VFD and motor. The reactor is an inductor that will filter out the high frequency voltage pulses. Measuring the voltage between the reactor and the motor will give results closer to what one expects from a sine wave voltage.

Measuring the power between the reactor and motor eliminates most of the power lost to heat as a result of the voltage PWM wave shape and thus more accurately measures shaft power.

THE TRANSDUCERS VOLTAGE

Use the OSI model series VT8. This true RMS measuring series has a frequency response from DC to 10 kilohertz and can handle the basic PWM frequency output of a VFD.

CURRENT

For full-scale currents up to 20 amperes, use the OSI model series CT8. These true RMS measuring transducers have a frequency range of DC through 500 hertz.

For full-scale current over 20 amperes, use the OSI model series CTL hall effect current transducers with the true RMS measuring signal conditioners such as the CTA213 for a 0 to 10 volt DC output or the CTA215 for a 4 to 20 mA DC output. The CTL series have a frequency range of 0 to 1 kilohertz and flat response to 5 kilohertz. This is more than adequate to handle VFDs.

POWER

Use the OSI model series P. This series comes supplied with CTL current transducers and is rated for 5 to 500 hertz operation. The CTL current transducers have flat frequency response from DC to 5 kilohertz. The frequency response of the voltage input is essentially flat from DC to 50,000 hertz. The P series is designed specifically for monitoring the power output from variable frequency drives and has a long and successful track record. (Note: the CTL current transducers supplied with the P series watt transducers cannot be used simultaneously for measuring current as the multiplication of voltage and current occurs inside these sensors.)

ADDRESSING THE PROBLEM OF WHAT THE USER REALLY WANTS TO MEASURE

Variable frequency drives as supplied today may provide a voltage output that is a nice clean sine wave or an unfiltered output with the carrier frequency. Carrier frequencies can range from a few kilohertz to as high as 30 kilohertz depending on the manufacturer. Please check with the manufacturer of the VFD that you are using. You should not have any measuring problems if:

- The VFD output is well filtered.
- There is a reactor between the VFD and your motor. Connect your transducers or instruments between the reactor and the motor.

If the output from the VFD is not filtered and a reactor is not being used you will, as described earlier, obtain higher than expected voltage and power readings.

These readings are not wrong but they do not reflect the work being done by the motor.

WHAT TO DO?

Solution 1

If the carrier frequency is in the kilohertz range, you might try adding a filter before the input to the voltage transducer and the watt transducer. A couple 0.2 mfd ceramic capacitors and a couple 100 ohm resistors wired as a pi network filter may work well filtering out the carrier.

Solution 2

Another approach is more sophisticated. Ohio Semitronics, Inc. builds a semi-custom monitoring package based on DSP technology. The firmware in this monitoring package determines the zero crossing of the synthesized sine wave and the envelope. From this, it is able to calculate all parameters.

Solution 3

This solution is a “cop-out” solution but very reasonable. If power is the primary concern, measure the power going into the VFD. This is considerably less expensive than measuring the variable frequency side. The VFD manufacturer should be able to give you an efficiency rating for the drive. From this rating and the power reading, you can calculate the power output from the motor.

ONLINE FAULT ANALYSIS OF DC MOTORS

David L. McKinnon, PdMA Corporation, Member, IEEE

Abstract – Over the last 20 years, Current Signature Analysis (CSA) has become an established tool for online fault analysis of AC Induction motors. Presently, very little research has been performed using current signature analysis on DC motors. This paper is a brief introduction to online fault diagnosis of DC motors using current signature analysis.

I. INTRODUCTION

This research initiative was undertaken to further develop online fault detection of DC motors using current signature analysis in both the time and frequency domains. These faults include differential current, shorted armature windings, shorted field windings, and off magnetic neutral plane brush positions. To detect the various faults in DC motors, we must develop a methodology to properly differentiate normal operating conditions from those of fault operating conditions. The first step is to establish a baseline of normal operating conditions. Once a baseline of normal operating conditions is established, a method of differentiating fault operating characteristics from baseline characteristics must be developed.

The primary differentiating methodology used in our study was a visual comparison of fault operating conditions to the baseline condition. For our study, a deterministic fault condition is considered one in which there is an obvious visual or numerical change in either or both the time or frequency domain. Visual changes may include variations in the waveforms in the time domain or the number of peaks, their amplitude, or their location in the frequency domain. For our purposes, numerically deterministic changes are those that exceed the measurement error sensitivity of the equipment in use by more than a specified amount beyond the maximum measurement error. For example, if the error sensitivity of the equipment is 1% of reading, and the specified change is 1%, the minimum fault differential required would be 2%.

II. DISCUSSION

A. TURN-TO-TURN SHORT

Many turn-to-turn or commutator bar-to-bar faults occur from carbon dust build up. Carbon dust from the brushes builds up on the commutator creating a short between commutator bars. To simulate the worst case of this fault condition, two wires that terminated on adjacent commutator bars were shorted together on the armature of the DC motor. The motor was then run and a current signature analysis in both the time and frequency domains was performed.

Figures 1 and 2 show a comparison of the current signatures in the time domain of a no fault condition to a turn-to-turn short (faulted condition). In the no fault condition, there is no modulation of the 120 Hz carrier frequency. In the fault condition shown in Figure 2, the waveforms have a modulation of the 120 Hz carrier of approximately 17 Hz.

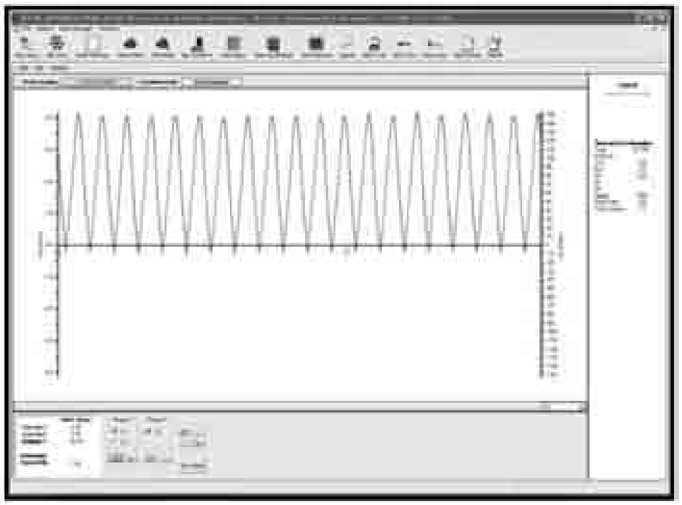


Figure 1. No fault – full load, full speed, and brushes at zero magnetic neutral axis.

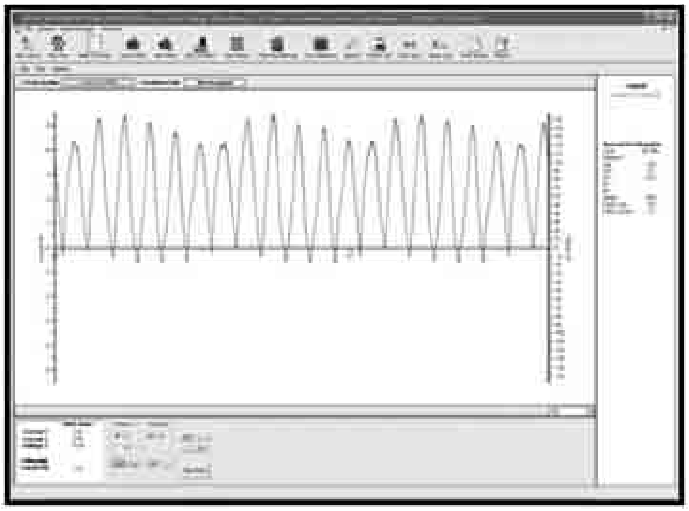


Figure 2. Turn-to-turn short – full load, full speed, and brushes at zero.

This fault condition is further noticed in the frequency spectrums shown in Figures 3 and 4. The frequency spectrum shown in Figure 3 is the no fault condition. Figure 4 shows the frequency spectrum of the turn-to-turn fault condition. Notice the dramatic increase in the harmonics throughout the spectrum.

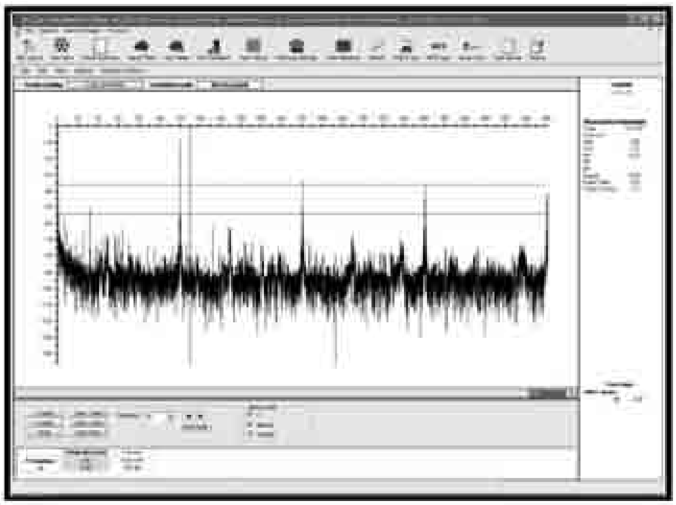


Figure 3. No fault – full load, full speed, and brushes at zero.

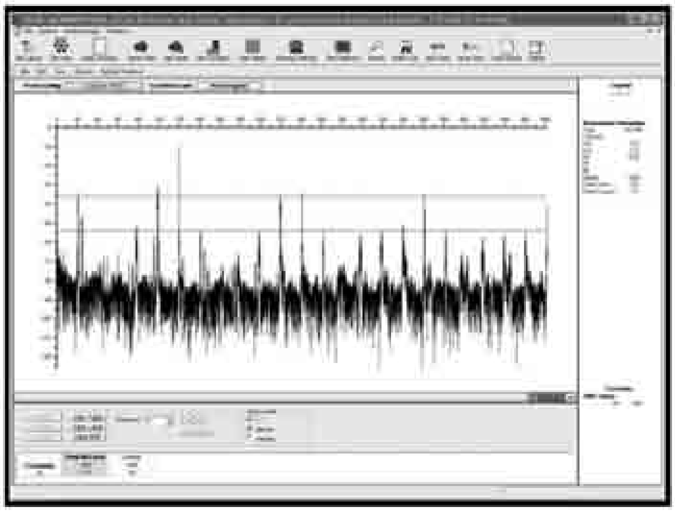


Figure 4. Turn-to-turn short – full load, full speed, and brushes at zero.

B. COIL GROUP SHORT

Figure 5 shows a fault operating condition in which an entire coil group is shorted. Notice this increase in modulation as compared to the turn-to-turn short shown in Figure 2.

Figure 6 shows the frequency domain of the coil group fault operating condition. There is a significant increase in the harmonics throughout the spectrum.

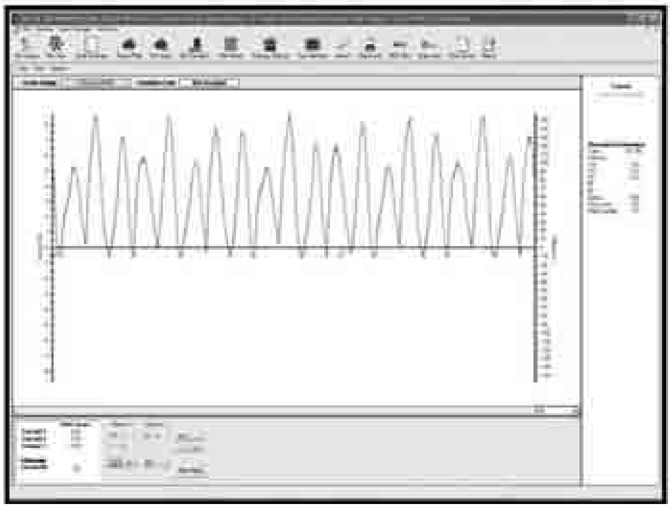


Figure 5. Coil group short – full load, full speed, and brushes at zero.

C. COIL TO COIL SHORT

Figure 7 shows the time domain of a fault operating condition in which two coil groups are shorted together. Notice the increase in modulation as compared to the coil group short shown in Figure 5. Figure 8 is the Frequency Spectrum produced by this fault.

D. BRUSH POSITION

Detecting when the brushes are off the magnetic neutral axis can be difficult, especially if the motor is inaccessible during operation. Using voltage analysis in the time domain makes the job of properly setting the brushes for the desired load much easier. The voltage waveforms in Figure 9 appear to be clean (i.e., without noise). When the brushes are off the magnetic neutral axis, the voltage waveforms in the time domain have a lot of hash as shown in Figure 10.

E. FIELD GROUND

To detect field winding grounds, the time domain waveform of the line to neutral voltage should be analyzed for anomalies. Under no fault conditions, the field voltage will be of significant amplitude as shown in Figure 11. When there is a field ground, the voltage will be very low as shown in Figure 12.

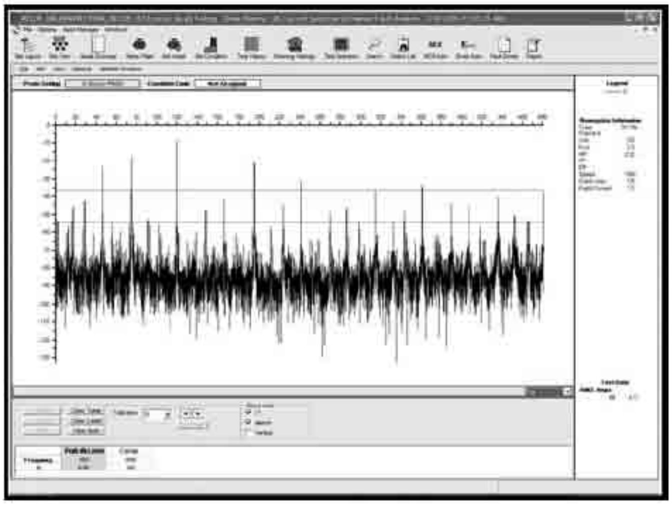


Figure 6. Coil group short – full load, full speed, and brushes at zero.

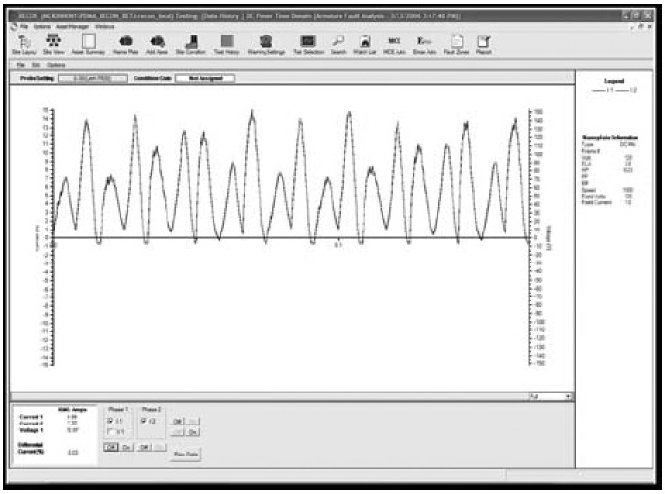


Figure 7. Coil to coil short – full load, full speed, and brushes at zero.

F. BRUSH GROUND

Brush grounds are very similar to field grounds. To detect a grounded brush, analyze the time domain of the line to neutral voltage waveform. Under no fault conditions, the field voltage will be of significant amplitude as shown in Figure 13. When there is a grounded brush,

G. DIFFERENTIAL CURRENT

Differential current may be analyzed by comparing two current waveforms in the time domain. There are two predominant situations where differential current analysis may provide insight to fault conditions that may otherwise be overlooked. One of these is when two or more cables feed a single terminal such as those found in semi-high current situations. Another situation differential current analysis may be used is in comparing the A1 to A2 currents. Situations may occur in which one of the main power cables may have bypass current.

Bypass current may occur from the high frequency switching found in DC drives. Differential current may also occur when alternate return paths offer a lower impedance than the primary feed cables.

Numerical analysis is the primary methodology used when analyzing differential current. The deterministic differential will vary according to the application. For our study, we used a 2% differential (1% equipment + 1% minimum differential) to compare two cables feeding a single terminal. One of these cables had a resistance inserted into the line to represent a high resistance connection of one of the cables in a multi-cable situation.

Figure 15 shows a situation of balanced currents between two cables connected to A1 terminal. Figure 16 shows a situation in which one of the cables connected to A2 terminal has a high resistance connected in series to simulate a high resistance connection. Note the 2.44% differential current met our established criteria of at least 2% for a fault condition to be deterministic.

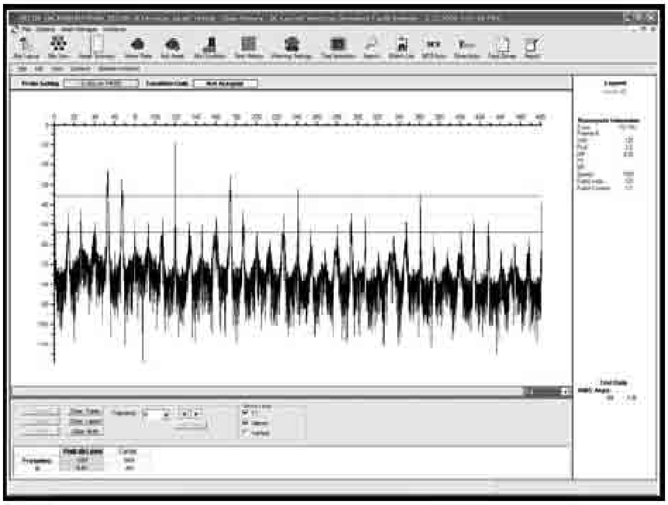


Figure 8. Coil to coil short – full load, full speed, and brushes at zero.

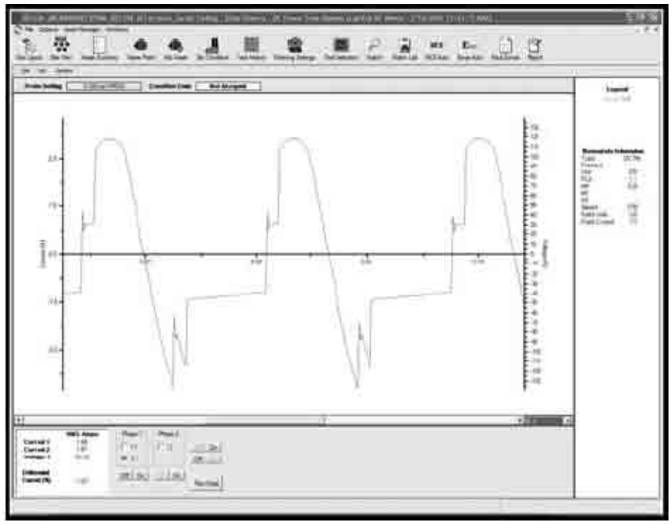


Figure 9. Brushes precisely on the magnetic neutral axis.

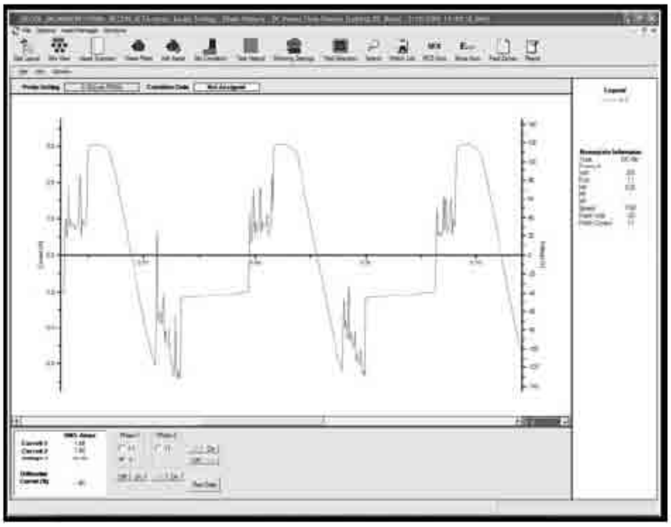


Figure 10. Brushes off magnetic neutral axis.

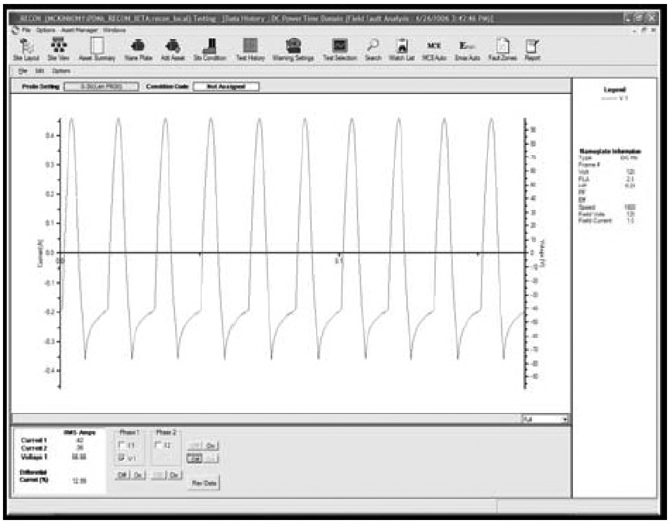


Figure 11. No field ground, tester grounded at drive.

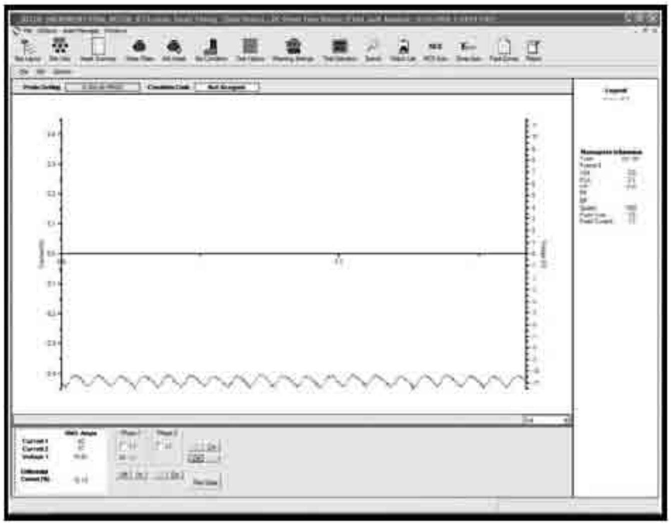


Figure 12. Field grounded to tester ground.

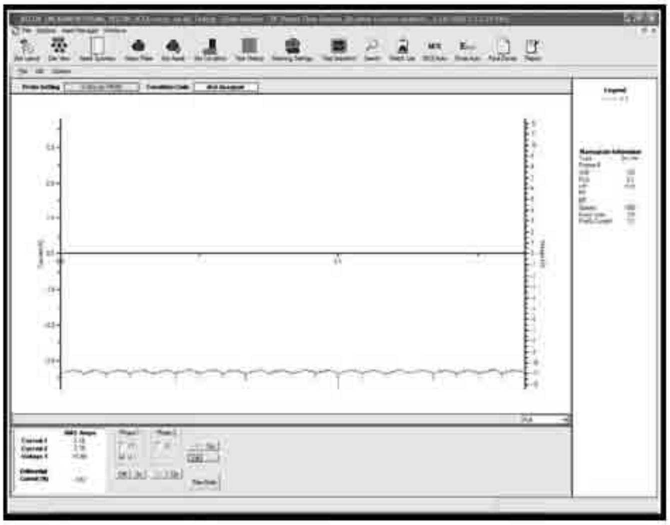


Figure 13. Brush grounded to tester ground.

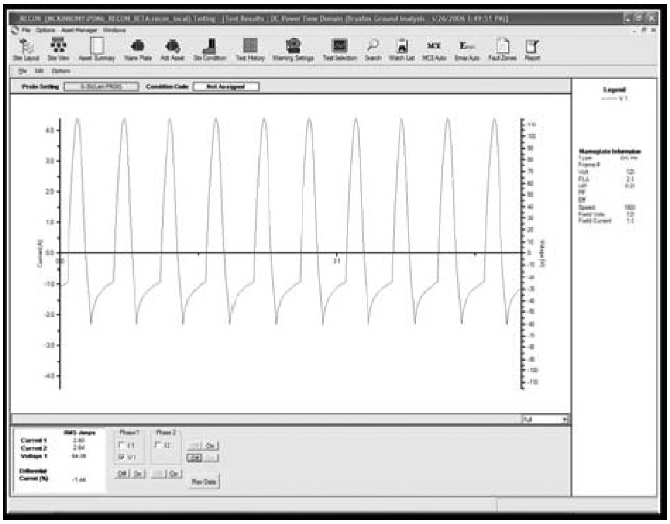


Figure 14. No brush ground, tester grounded at the drive.

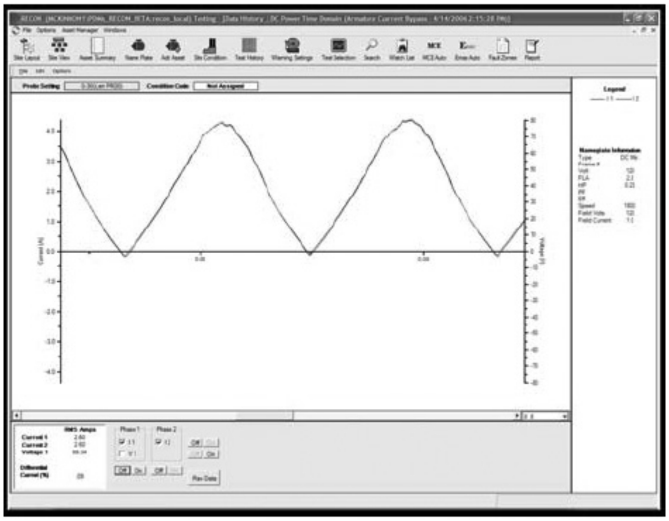


Figure 15. No fault condition – 0.09% differential current.

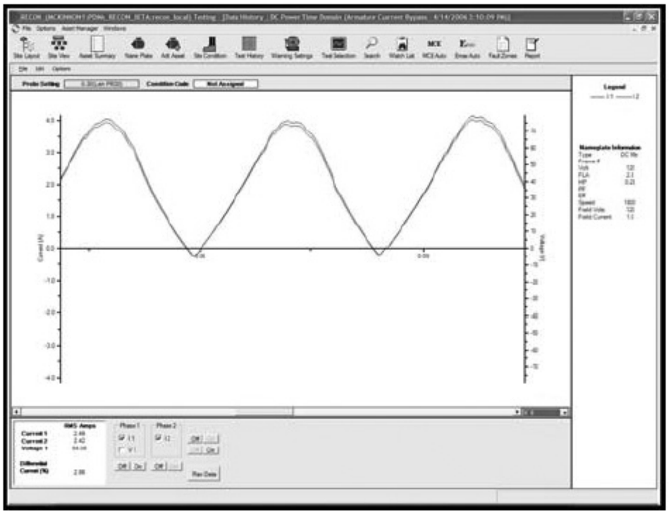


Figure 16. High resistance fault condition – 2.44% differential current.

III. SUMMARY

Our research has shown the use of current and voltage signature analysis in both the time and frequency domains may provide useful insights to online fault analysis of DC motors. Many common faults such as shorted turns or commutator bars, grounded windings, and off magnetic neutral axis faults may be detected using online current and voltage signature analysis. Trending these over time may provide an indication of a developing fault in the motor. As with all tests, cross correlation between technologies is imperative in the decision making process.

IV. REFERENCES

1. S. J. Chapman, “Electric Machinery Fundamentals”, McGraw-Hill publishing Company, 1985.

2. S. Smith, “Magnetic Components Design and Applications”, Van Nostrand Reinhold Company,

INDUCTION MOTORS: – PROTECTION

S.E. Zocholl, Schweitzer Engineering Laboratories, Inc.

THERMAL PROTECTION

Manufacturers of motor relays have used Resistance Thermal Detectors (RTDs) to try to protect motors from thermal damage. Unfortunately, the slow response of RTDs reduces their value. Users must instead rely on inverse time-phase overcurrent elements and a separate negative-sequence overcurrent element to detect currents that could lead to overheating. Neither time overcurrent protection nor RTDs account for thermal history or accurately track the excursions of conductor temperatures.

An element should be used that accounts for the slip dependent I2r heating of both positive- and negative-sequence current. The element is a thermal model, defined by motor nameplate and thermal limit data. This mathematical model calculates the motor temperature in real time. The temperature is then compared to thermal limit trip and alarm thresholds to prevent overheating from overload, locked rotor, too frequent or prolonged starts, or unbalanced current.

What data defines the thermal model? Full load speed, the locked rotor current and torque, and the thermal limit time define it. What does torque have to do with the thermal model?

The I2r heat source and two trip thresholds are identified by the motor torque, current, and rotor resistance versus slip shown in Figure 1. It shows the distinctive characteristic of the induction motor to draw excessively high current until the peak torque develops near full speed. Also, the skin effect of the slip frequency causes the rotor resistance to exhibit a high locked rotor value labeled R1 which decreases to a low running value at rated slip labeled R0.

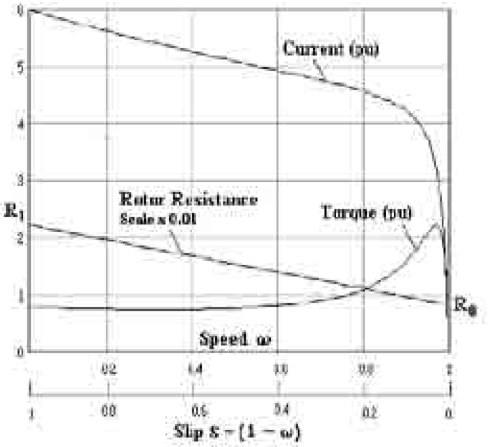


Figure 1: Current, Torque, and Rotor Resistance of an Induction Motor Versus Speed

A typical starting current of six times the rated current and a locked rotor resistance R1 of three times the value of R0 causes the I2r heating to be 62 x 3 or 108 times normal. Consequently, an extreme temperature must be tolerated for a limited time to start the motor. A high emergency I2t threshold is specified by the locked rotor limit during a start, and a second lower threshold for the normal running condition is specified by the service factor. Therefore, the thermal model requires a trip threshold when starting, indicated by the locked rotor thermal limit, and a trip threshold when running, indicated by the service factor.

How is the heating effect of the positive- and negative-sequence current determined? The positive-sequence rotor resistance is plotted in Figure 1 and is calculated using current I, torque QM, and slip S in the following equation:

$$R_r = \frac{Q_M}{I^2} S \qquad (1)$$

It is represented by the linear function of slip shown in Figure 1. The positive-sequence resistance Rr+ is a function of the slip S:

$$R_{r+} = (R_1 - R_0)S + R_0 \qquad (2)$$

The negative-sequence resistance Rr- is obtained when S is replaced with the negative-sequence slip (2-S):

$$R_{r-} = (R_1 - R_0)(2 - S) + R_0 \qquad (3)$$

Factors expressing the heating effect of positive- and negative-sequence current are obtained by dividing Equations 36 and 37 by the running resistance R0. Consequently, for the locked rotor case, and where R1 is typically three times R0, the heating effect for both positive- and negative sequence current is three times that caused by the normal running current.

$$\left.\frac{R_{r+}}{R_0}\right|_{S=1} = \left.\frac{R_{r-}}{R_0}\right|_{S=1} = \frac{R_1}{R_0} = 3 \qquad (4)$$

For the running case, the positive-sequence heating factor returns to one, and the negative sequence heating factor increases to 5:

$$\left.\frac{R_{r+}}{R_0}\right|_{S=0} = 1 \quad \left.\frac{R_{r-}}{R_0}\right|_{S=0} = 2\left(\frac{R_1}{R_0}\right) - 1 = 5 \qquad (5)$$

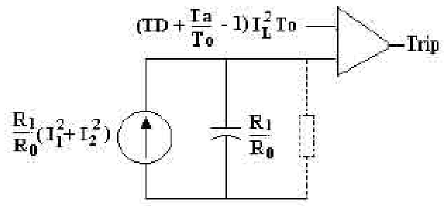
These factors are the coefficients of the positive and negative currents of the heat source in the thermal model.

STARTING AND RUNNING STATES OF THE THERMAL MODEL

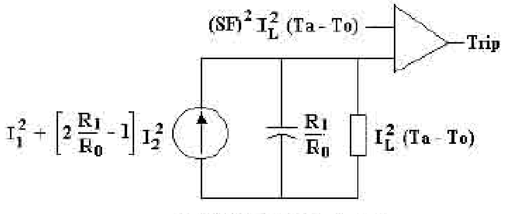
Because of its torque characteristic, the motor must operate in either a high current starting state or be driven to a low current running state by the peak torque occurring at about 2.5 per unit current. The thermal model protects the motor in either state by using the trip threshold and heating factors indicated by the current magnitude. The two states of the thermal model are shown in Figure 2. The thermal model is actually a difference equation executed by the microprocessor. However, it can be represented by the electrical analog circuit shown in Figure 2.

In this analogy, the heat source is represented by a current generator, the temperature is represented by voltage, and thermal resistance and capacitance are represented by electrical resistance and capacitance. The parameters of the thermal model are defined as follows:

R1 = Locked rotor electrical resistance (per unit ohms)
R0 = Running rotor electrical resistance also rated slip (per unit ohms)
IL = Locked rotor current in per unit of full load current
Ta = Locked rotor time with motor initial at ambient
To = Locked rotor time with motor initially at operating temperature


$(TD + \frac{Ta}{To} - 1) I_L^2 To$
Trip
$\frac{R_1}{R_0}(I_1^2 + I_2^2)$
$\frac{R_1}{R_0}$

(a) Starting State I > 2.5 pu



(b) Running State I < 2.5 pu

Figure 2. States of the Thermal Model

The starting state is shown in Figure 2a and is declared whenever the current exceeds 2.5 per unit of the rated full load current and uses the threshold and heating factors derived for the locked rotor case. Thermal resistance is not shown because the start calculation assumes adiabatic heating. The running state, shown in Figure 2b, is declared when the current falls below 2.5 per unit current and uses the heating factors derived for the running condition. In this state, the trip threshold "cools" exponentially from a locked rotor threshold to the appropriate threshold for the running condition using the motor thermal time constant. This emulates the motor temperature which cools to the steady state running condition.

In the model, the thermal limit IL 2Ta represents the locked rotor hot spot limit temperature and IL2 (Ta – To) represents the operating temperature with full load current. The locked rotor time Ta is not usually specified but may be calculated by using a hot spot temperature of six times the operating temperature in the following relation:

$$\frac{I_L^2 T_a}{I_L^2 (T_a - T_o)} = 6 \therefore \frac{T_a}{T_o} = 1.2 \qquad (6)$$

There are two reasons for using the rotor model in the running state. The first is that the rotor model accounts for the heating of both the positive- and the negative-sequence current and conserves the thermal history at all times throughout the starting and running cycle. The second is that it is an industry practice to publish the overload and locked rotor thermal limits as one continuous curve as illustrated in Figure 3. Figure 3 is the time-current characteristic of the thermal 4 model plotted with the motor initially at ambient temperature. Despite the difference in input watts and thresholds, the characteristics of the running and starting states plot as a continuous curve. This condition occurs when the locked rotor threshold is set at 0.8 of IL2. Ta and the motor service factor is 1.2.

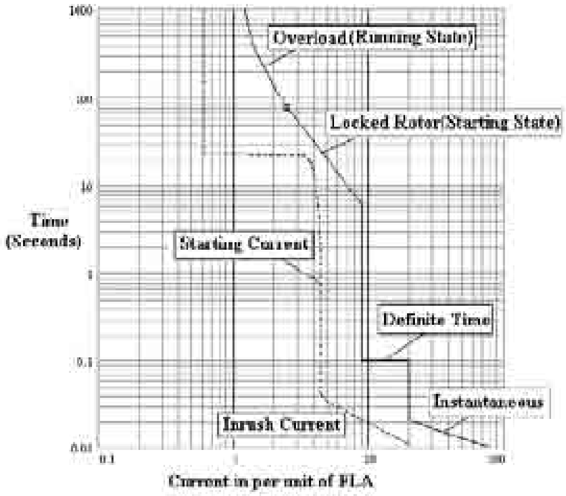


Figure 3. Motor Characteristic and Starting Current

As a final refinement, assigning standard values of 3 and 1.2 to the ratios R1/R0 and Ta/To, respectively, allows the model parameters to be determined from five fundamental settings:

FLA	Rted full load motor current in secondary amps
LRA	Rted locked rotor current in secondary amps
LRT	Termal limit time at rated locked rotor current
TD	Time dial to trip temperature in per unit of LRT
SF	Motor rated service factor

The thermal circuit derived in this paper and shown in Figure 2 is covered by U.S. Patent No.5,436,784.

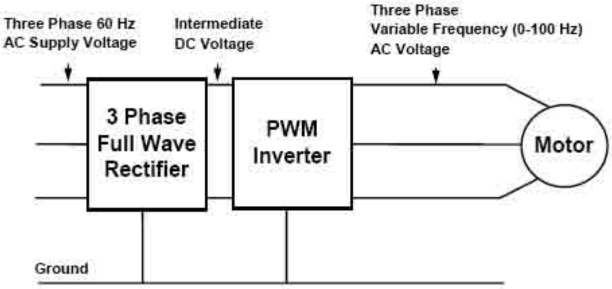
FAULT PROTECTION

In addition to the thermal element described above, definite-time and instantaneous phase and ground elements provide protection for faults in the motor leads and internal faults in the motor itself. The characteristics of these elements are plotted in Figure 3. A definite-time setting of about 6 cycles allows the pickup to be set to 1.2 to 1.5 times locked rotor current to avoid tripping on the initial Xd" inrush current (shown magnified). The instantaneous element is set at twice the locked rotor current for fast clearing of high current faults. Similar definite-time and instantaneous elements provide for ground fault protection.

VFD CABLES

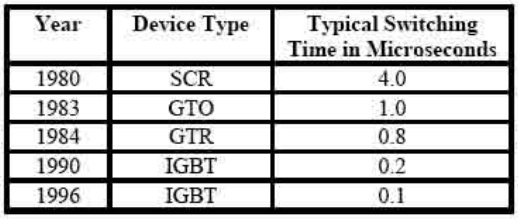
Wire and Cables Group, Anixter

Variable frequency adjustable speed motor drives (VFDs) usually employ a method of motor control called PWM (pulse width modulation) using semiconductor devices called IGBTs. "IGBT" stands for insulated gate bi-polar transistor. VFDs are also often referred to as adjustable speed drives (ASDs) or as AC (alternating current) drives. AC drives, as opposed to older DC (direct current) types, are used for most new installations as well as for replacement in many industrial applications. An electrical diagram of a typical VFD system is shown. In practice, the 3-phase, full wave rectifier and the PWM inverter are usually mounted within a single metal enclosure. VFD technology reduces the size and increases the efficiency of ASDs and, at the same time, improves control of the motor's speed and torque. However, VFD technology also has a few undesirable side effects that must be managed.



Due to the laws of physics, the fast switching speeds of the semiconductor devices used in VFDs (see table below) inherently create EMI (electromagnetic interference) which can be radiated by the inverter-to-motor power cable. With today's fastest devices, the electrical energy flowing in the cable contains components with frequencies as high as 30 MHz (megahertz). If this RF (radio frequency) energy is not contained, the radiated energy can interfere with the proper operation of nearby electronic equipment. The more electronics in a facility, the greater the risk of problems.

The design of the cable used with VFDs, along with proper installation, plays a key role in controlling these side effects.



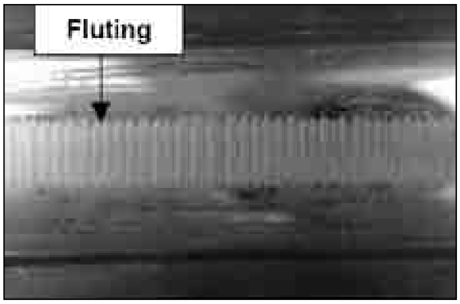
Year	Device Type	Typical Switching Time in Microseconds
1980	SCR	4.0
1983	GTO	1.0
1984	GTR	0.8
1990	IGBT	0.2
1996	IGBT	0.1

WHAT ARE THE ISSUES?

About a dozen industry studies have been conducted regarding the role that power cables play in the safe and reliable operation of VFD systems. In one of the larger studies, extensive testing of 150-foot lengths of eight different cable constructions was performed on a 50 horsepower VFD system installed at a test laboratory in Helsinki, Finland.[1] In another major study, the magnitude and effect of reflected waves in the cable were studied extensively.[2]

Overall, the studies focused primarily on the following VFD cable concerns:

- EMI radiated by the VFD's inverter-to-motor power cable which might interfere with the proper operation of other nearby electronic equipment
- Stray electrical currents which can flow through both the drive's grounding system and the motor's bearings and cause premature bearing failure through a process called fluting (see photo).



- High voltage reflections that can occur with certain drive system configurations and that might cause early failure of the inverter-to-motor power cable The last item, high voltage reflections, has caused a significant number of in-service motor failures. These failures have lead to the development of motors that are specifically designed for use with VFDs. On the other hand, very few cable failures have been confirmed but there is concern over possible long-term cable damage – especially on VFDs operating at 575 volts and above.

EMI

The fast switching speeds of the solid-state (semiconductor) devices used in VFDs increase the potential for EMI (electromagnetic interference). The drive's solid-state electronics generate RF energy which can be radiated by the drive's inverter-to-motor power cable and picked up by nearby circuits. This interference can cause malfunctions in sensitive electronics. As a result, VFD manufacturers usually recommend the use of a shielded power cable between the drive electronics and the drive motor to contain this RF energy.

Fortunately, adequate shielding can be obtained with existing cable technology using impervious corrugated aluminum armor as the shield. This type of armor is often called “CCW” for continuously corrugated and welded. Other shield types such as copper tape, copper braid or aluminum/polyester foils can also be used with slightly reduced effectiveness. The effectiveness of cable shields is typically determined by measuring the transfer impedance using NEMA test method WC61.[3] A cable shield with a transfer impedance of less than 100 m_/m (milliohms per meter) is generally considered to be a “good” shield and one with less than 10 m_/m an “excellent” shield. Impervious corrugated aluminum armor typically has transfer impedance in the range of 1 to 10 m_/m from DC to 30 MHz, the frequency range of interest for VFD applications. Most other common shield types provide a transfer impedance in the range of 10 to 100 m_/m.

STRAY GROUND CURRENTS

A second concern is that stray electrical currents in the VFD’s grounding system may flow though the drive motor’s main bearings. It is well known that the flow of electrical current through motor bearings in the milliamp range can cause premature bearing failure.

Motor bearing currents can be minimized by using an inverter-to-motor power cable with three symmetrically positioned grounding conductors in combination with a low impedance shield. Such a design minimizes the total current that is induced in the grounding system by current flowing in the phase conductors and, ultimately, the amount of stray current that flows through the motor bearings.

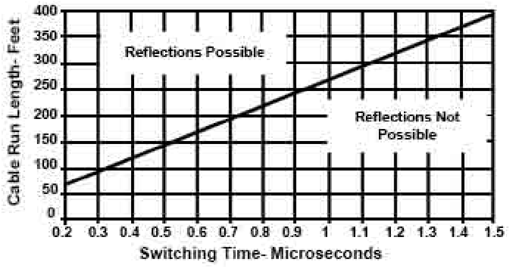
HIGH VOLTAGE REFLECTIONS

A third concern is that the high frequencies generated by the VFD, coupled with long cable runs between the VFD and the drive motor, can result in reflected waves in the cable.

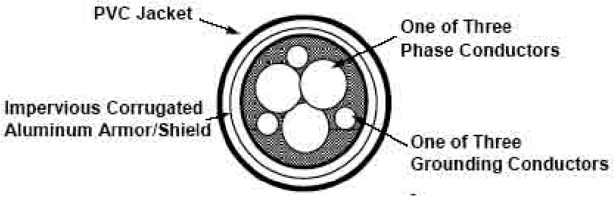
Reflected waves can produce abnormally high voltages in the cable. Peak voltages of up to 2.5 times the nominal system voltage have been measured on VFD power cables.

Because of these high voltage pulses, the use of 2000 volt rated cables is recommended on some 600 volt drive systems.

For most VFDs operating at 480 volts or below, the recommended cable rating is 600 volts. However, 575 volt VFDs sometimes require a cable with a higher voltage rating, depending on cable length and drive switching time. To determine the recommended cable voltage rating for a 575 volt drive system, refer to the graph below to determine if reflections are possible. (If a reactor or a low pass filter is used with the drive, the longer switching time resulting from the use of this device can be used.) If reflections are possible, a 2000 V rated cable is recommended. If not, a 600 V rated cable is usually adequate. If inverter switching time or cable length is unknown at the time the cable is specified, a conservative approach is to specify a 2000 V rated cable in either case.



The winner of the sweepstakes for “best overall cable for VFD applications” is a three conductor, impervious corrugated aluminum armor (CCW) cable with three symmetrically positioned grounding conductors as illustrated below. (In small sizes such as 10, 12, and 14 AWG cables, only one ground wire is required because the effect of stray ground currents is small.) Southwire’s Armor-X® cable with three grounds is such a cable when installed with appropriate armor fittings in accordance with the NEC.[4] Anixter’s catalog numbers for this and other VFD cable types are given in Anixter’s VFD cable brochure # 251921.


PVC Jacket
One of Three Phase Conductors
Impervious Corrugated Aluminum Armor/Shield
One of Three Grounding Conductors

Notes:

[1] “Evaluation of Motor Power Cables for PWM AC Drives” by J. M. Bentley and P. J. Link, ABB Industrial Systems Inc., IEEE Pulp and Paper Industry Conference, IEEE publication # 0-7803-3148-6-5/96, pages 55-69.

[2] “Riding the Reflected Wave – IGBT Drive Technology Demands New Motor and Cable Considerations” by L. A. Saunders and G. L. Skibinski, Allen-Bradley Company; S. T. Evon, Reliance Electric; and D. L. Kempkes, Chevron USA Offshore, IEEE Petroleum and Chemical Industry Conference, IEEE publication # 96-CH35988-6/96/0000-0075, pages 75-84.

[3] NEMA WC61, Transfer Impedance Testing, National Electrical Manufacturers Association, www.nema.org

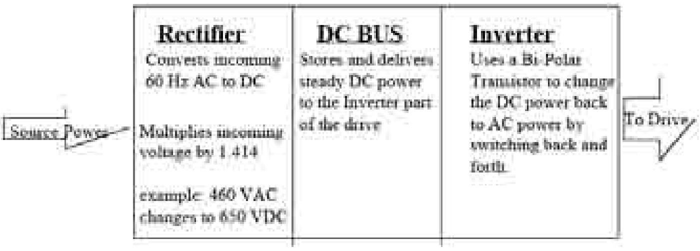
[4] NFPA 70, National Electrical Code, National Fire Protection Association, www.nfpa.org

VFD SYSTEMS AND CABLE

LAPP USA Inc.

BACKGROUND

VFD is the acronym for Variable Frequency Drive, which has become a very popular method to adjust a motor's speed. Frequency can be defined as an electrical term meaning power pulses of voltage and current. In the United States, 60 Hertz, or 60-power pulse cycles per second, are conducted through most wires and cables throughout the country. As the power in the United States is alternating current (AC), each of these frequency cycles contains one positive and one negative power pulse of voltage and current. Increasing the number of power pulses per second will make the motor turn faster. Likewise, decreasing the number of power pulses per second will make the motor turn slower. Therefore, by increasing and decreasing the frequency of the power pulses, the drive can adjust the speed of the motor.



Rectifier	DC BUS	Inverter
Converts incoming 60 Hz AC to DC Multiplies incoming voltage by 1.414 example: 460 VAC changes to 650 VDC	Stores and delivers steady DC power to the Inverter part of the drive	Uses a Bi-Polar Transistor to change the DC power back to AC power by switching back and forth

The components of the drive system are broken into four major categories: Source power, VFD, Cable and the Motor. Other ancillary components exist such as resolver and encoder feedback devices, tachometers, sensors, relays and others that help supplement the system.

The local electrical company provides the source power for all electrical equipment and apparatus for operation. The source power may go through a transformer to either increase or lower the voltage, but the frequency will remain constant at 60 Hertz.

The function of the drive is to send all power pulses that control the motor's start-up, operating speed, and stopping. The three major tasks that a VFD drive has to accomplish prior to adjusting a motor's speed are:

First, the source power must be converted from Alternating Current (AC) to Direct Current (DC). This conversion is accomplished by means of a rectifier; a diode is used for simple rectifying and a Silicone Controlled Rectifier (SCR) is used for more intelligent rectification. The power source that was 600 Volts AC, 60 Hertz now is converted to 650 Volts DC. This AC to DC conversion is necessary before the power can be changed back to AC at a variable frequency. In short, the power goes from AC to DC then back to AC again so it can be used for VFD applications.

Second is a large capacitor, which is known as the DC bus. A capacitor can be simply defined as an electronic component that stores energy. The DC bus acts like a storage battery to supply DC power to the third part of the drive.

The third part of the drive is known as the inverter. An inverter converts DC back to AC by utilizing an electronic component known as a Bi-polar transistor. The inverter can be controlled to vary the frequency so that the motor receives the correct flow of power pulses. This is the advantage of utilizing a Variable Frequency Drive. The pulse width modulation (PWM) frequency is approximately 20,000 Hertz and offers finer control by only varying a few cycles. In contrast at the power source frequency of 60 Hertz, changing a few cycles only offers a much coarser change and will not allow for as close control.

The VFD drive output is basically a flow of AC power pulses at a certain frequency that provides or maintains the desired speed of a running motor. The motor, through means of power supply cables, receives these power pulses. Cables and their functions will be discussed later.

The motor consists of two major parts: the armature (rotor) physically turns, and the field (stator) that remains stationary. The cables are connected to the stator and, upon the application of power, cause an electromagnetic field to rotate. This rotating field causes the rotor to follow the moving electromagnetism and turn.

The stator of the motor is constructed of insulated wire that is wound through slots a specific number of times in a required pattern. This is the defenseless part of the motor. The wire insulation is extremely thin and can get nicked during the winding process. These nicks are the bare spots in the wire that causes arcing and can lead to motor failure.

WHAT HAPPENS

The VFD drive transition from AC to DC then back to variable AC is not done cleanly. Power distortions are created by the first part of the drive (rectifier) and then sent back through the source power system. Power distortions are also created by the third part of the drive (inverter) and sent on to the motor.

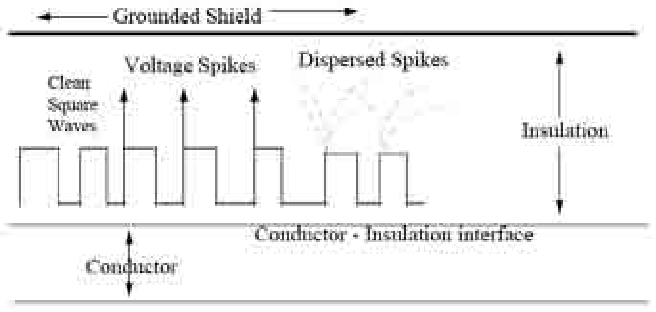
Therefore, power distortions are created at both ends of the drive causing nonlinear spikes, wave reflections and inrush currents. The following will explain these types of phenomena:

Harmonics, non-linear spikes, and reflections are common power distortions. Inrush currents is an additional problem that the motor and cable are subjected to. Harmonics are multiples of a fundamental frequency. As an example, if the fundamental frequency is 60 Hertz, the 5th harmonic is 300 Hertz (5x60). Power distortions are caused by harmonic frequencies. Some harmonic frequencies are "in-phase" with the fundamental frequency and rotate in the same direction as the field, except more quickly due to the higher harmonic frequency. This condition causes the power, both voltage and current of each harmonic to add to the voltage and current of the fundamental frequency. Keep in mind that the power in the fundamental frequency is all that is needed or wanted. The additional power from the harmonic frequencies causes overheating, high voltage stress and also confuses electronic functions that depend on the fundamental frequency for clock or timing functions. The added harmonic power also affects the motor and power supply cables.

As previously mentioned, a higher flow of power pulses will cause a motor to run faster. Harmonic frequencies cause a motor to fine-tune its adjustments with braking and other heat generating reactions. The 7th and 13th harmonics rotate with the field, supply additional power pulses and require the brake to regulate motor speed. The 5th and 11th harmonics oppose the field's rotation and require additional current (heat) to regulate motor speed. The 3rd, 9th, & 15th are triple harmonics which do not rotate but are the most in-phase and additive to neutral current (heat). The harmonics that are commonly generated by a VFD drive are the 5th, 7th 11th, and 13th.

The definition of non-linear power is that a change in voltage does not generate the same change in current. The motor expects a power pulse to be regulated. When the frequency is increased, the motor expects the right amount of current to be included in the power pulse to sustain the increase in speed. In the case of non-linear power, the current does not properly support the motors requirements. This distorted current either fights or overdoes the change, resulting in high voltage stress and heat.

A spike is a very quick increase in voltage that occurs for a short time. The inverter in the drive which is a fast switching transistor must rise from zero to 650 volts (rectified 460 volt system) and then go back to zero 20,000 times a second. This is a very fast rise time. Several things can happen as the inverter is switching and conducting the power pulses through the cable to the motor. The 650-volt normal voltage can overshoot higher to 2,000 volts or more. The cable that connects the VFD drive to the motor looks electrically different to the power pulse as the length increases. The longer the cable length, the greater the increase in inductance which, in turn, affects the overshoot of the voltage spike. Therefore, a long power supply cable will have greater and more intense voltage spikes than a shorter cable. Voltage spikes are very quick lasting for only a few millionths of a second. The inverter in the drive is called an Insulated Gate Bipolar Transistor (IGBT) and is one of the fastest switching inverters in the Pulse Width Modulation (PWM) type of variable frequency drives.



Frequency waves that seem to be standing still are reflections and are often called standing waves. As a comparison, this would be similar to seeing a spinning wheel that appears to be frozen but actually is in motion. At the cable attachment to the motor, the standing wave sees a large difference in impedance and can be reflected back to the drive. A long power supply cable allows for more opportunity for a reflected standing wave to get in phase with itself at a certain point in the cable and double the voltage and current there. The 650-volt normal voltage now becomes 1,300 volts and the current also doubles. At this spot, the insulation is severely stressed and will, in time, overheat and puncture, causing the cable to fail.

During motor start-up, inrush currents occur. The motor and power supply cable act as a large capacitor that must be charged up to the normal operating power level. When a motor is first energized, it can draw up to six times its full load running power requirements. The cable must be of adequate conductor AWG size so there will not be any significant voltage drop.

When the current in power pulses from a source circuit ends up in the power pulses of another circuit, capacitive coupling takes place. This is caused from a changing electric field in the source circuit. The change in voltage, from zero to full and back to zero, causes the current to flow and couple from one copper conductor to another. In short, power pulses from one circuit are added to compatible pulses of another circuit that result in heat and stress.

LAPP VFD CABLE

The Lapp VFD cable is different from ordinary motor power supply cable because it can disperse all of the spikes that the VFD drives generate. The cable construction starts with a unique semiconductive composite insulation applied over the conductor. The use of a semi-conductive layer will be discussed in later in greater detail.

The color of the insulation on three conductors is black and each conductor is identified with white numbers, the fourth conductor is colored green/yellow for purposes of grounding. All conductors are rated for 1000 volts and 3000 volts peak. This enables the cable to withstand reflections, standing waves, and spike voltages that a VFD cable may experience under typical conditions of use. Lapp VFD cable is both UL and CSA approved and is available in conductor size range from 18 AWG up to 2 AWG. Other combination of conductors and different AWG sizes can also be made upon request.

Part of the standard VFD cable design incorporates an inner jacket to help provide an additional layer of protection between the insulation and braid shield and also lowers the capacitive interaction between the braid and power conductors. The inner jacket is also sized to fit an MSSC type shielding connector for full circumferential 360° grounding of the shield. The outer jacket is also flame resistant, has superior resistance to oils and helps provide overall optimum cable impact and crush resistance. A single jacketed version is also available for those applications requiring UL and CSA Tray cable approval.

WHY A SEMI-CONDUCTIVE LAYER?

The application of a semi-conductive compound over an electrical conductor is a process that has been in practice for years. Semi-conductive compounds are available both in thermoplastic or thermosetting types to complement the type of insulation system that is being used in the cable. As Lapp VFD cables are primarily insulated with polyvinylchloride, the semi-conductive compound is of a thermoplastic type.

About a half-century ago, engineers in the cable industry became aware that the simple cable design of conductor/insulation/shield was voltage limited in the aspects of safety and long-term trouble free operation. The problem arose from where the conductor met the primary layer of insulation and the creation of voids that occurred where the insulation did not fully penetrate into the small spaces in the outer layer of the stranded conductor. This resulted in unwanted corona discharge across these voids which, in turn, led to the quick deterioration of the insulation.

Another problem was the small diameter of the individual wires in the outer conductor layer and their surface irregularities which produced points of high electrical stress, again attributing to rapid deterioration of the insulation.

In order to resolve these problems, the use of semi conductive compounds as a stress-relieving layer between the conductor and primary insulation was introduced. The application of an extruded semi-conductive compound provided a rounder and smoother continuous layer and also completely filled in all areas of the outer layer in the stranded conductor. In short, the extruded semi-conductive layer now provided complete and void free contact between the conductor and primary insulation. The use of extruded semi conducting compounds now alleviated many problems of the past and resulted in improved cable reliability, extended life, breakdown voltages and corona levels.

Semi-conductive material extruded over the conductor is a very common process used in the high-voltage cable industry to help maintain the cable's overall performance while under extreme conditions. Likewise, the application of the semi-conductive layer over the conductor helps to relieve electrical stress that is experienced by the Lapp VFD cable during periods of high-voltage spikes. The semi-conductive layer disperses the high-voltage spike so that the primary insulation is not damaged. Therefore, no degradation to the primary insulation begins and the cable remains in operation with no disruption in service. All Lapp PVC insulated VFD cables have an extruded thermoplastic sem-conducting layer applied directly over the conductor which helps to insure long service life and trouble free operation.

Other cable companies that use semi-conductive insulation are involved with the manufacture of high-voltage cables. These manufacturers provide cables to customers such as major utilities and power companies. Depending upon the manufacturer, these companies offer cables that use semi-conductive insulation in their designs for cables that are rated for 5,000 to 138,000 Volts. Some these High-Voltage cable manufacturers include:

- The Okonite Company
- General Cable
- USA Wire & Cable, Inc.
- Nexans Energy
- Kerite

WHAT IS CORONA?

Corona is the ionization of the nitrogen in the air caused by an intense electrical field. Corona can be detected as a crackling or hissing type of audible sound and it also produces light, which can be seen by the naked eye in darkness.

WHY IS CORONA NOT GOOD FOR INSULATION?

Corona causes ozone and also nitric acid that occurs in the presence of moisture in the air and then accumulates as a white or dirty powder on the insulator. When the nitric acid accumulates, micro arcing occurs, creating carbon tracks across the insulating material.

This can lead to defects in the insulating material over time, eventually causing cable failure.

WHAT IS CORONA INCEPTION VOLTAGE?

The voltage level at which corona initiates or begins.

WHAT IS CORONA EXTINCTION VOLTAGE?

The voltage level at which corona ceases or stops.

HOW IS CABLE TESTED FOR CORONA?

One method of testing cable for corona levels is indicated by the equipment and procedure below:

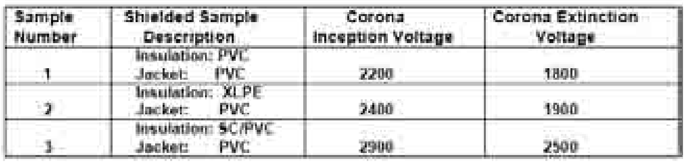
Apparatus Required:
1. AC Power Supply
2. Voltage measuring device
3. Discharge measuring device
4. Cable sample

Proper connections are made so that when voltage is applied to the cable sample, both voltage and discharge levels can be measured. The cable samples tested were 50 ft. in length and the threshold used for inception and extinction was 5 Pico coulombs. The discharge-measuring device will display corona inception and extinction levels occur by means of an oscilloscope. The voltage-measuring device will display the corona inception and extinction voltage levels. Voltage is applied gradually to the cable sample until the corona inception has been reached, then the voltage is gradually reduced until the corona extinction has been reached.

LAPP VFD TESTING

Several cables were tested at an independent third party facility using ICEA T-24-380 as the reference test specification. Three 12 AWG four conductor samples were tested as shown below:

Both corona inception and extinction voltage levels were significantly higher for sample 3 when compared to both samples 1 & 2. Sample 3 used Lapps unique primary insulation construction of a semi-conductive thermoplastic layer applied directly over the conductor with a PVC insulating covering. In short, the higher the corona inception and extinction levels, the better long-term protection a cable has to offer when exposed to high-voltage conditions that are experienced with VFD cables.



Sample Number	Shielded Sample Description	Corona Inception Voltage	Corona Extinction Voltage
1	Insulation: PVC Jacket: PVC	2200	1800
2	Insulation: XLPE Jacket: PVC	2400	1900
3	Insulation: SC/PVC Jacket: PVC	2900	2500

THE PROBLEM WITH CABLE

Basically, with VFD systems the cable itself is the hardest component to check out. A drive has a self-diagnosis program and a shorted motor can be easily detected. A voltage spike only lasts a few millionth's of a second and is seldom actually recognized at the time of cable failure. The equipment just drops off line. A restart is usually possible if the cable damage is not severe enough to prevent system operation. When a cable's insulation is punctured from high-voltage stress, the current then travels through the hole in the insulation to the nearest ground path, which is usually the braid shield. When the current from a hot phase conductor touches a grounded braid, an extreme amount of current is created. This is too much current for the shield to carry away fast enough, so the braid quickly heats up and burns. The braid will burn as long as the current can arc to it. Once the hole in the braid is burned big enough, the cable will self heal until the next high-voltage stress puncture occurs at a different spot.

Eventually, the arcing that occurs will burn through the conductor and the cable damage will be detected by ordinary testing. But significant time has been lost from checking the motor and the drive. Up until the final failure, the cable may not show any defect if it has burned clear and is tested without using special cable insulation test apparatus. Once a cable is found to have failed, it is another matter to remove, replace and put connectors on the cable. The Lapp VFD cable's ability to disperse the failure causing spikes will prevent downtime delays that are associated with other typical motor power supply cables.

THE VFD SYSTEMS SOLUTION

All four parts of the VFD drive system meet some fairly rigorous requirements to help insure safety and uninterrupted operation. Since 1996, the National Electrical Code Article 430-22a has specified that source power conductors are required to be sized at 125% of the full load current of the drive. This requirement was established to protect the cables from power distortions generated by the rectifier.

Having the pulse rate changed or switching the drive inverter transistor to a slower frequency can eliminate the higher power low number harmonics. To clean off the harmonics and block the spikes filters, reactors and isolation transformers can be added to the drive. In an effort to lower the inrush currents, startups can be made more gradual. These add-ons could be cost prohibitive and cause further voltage drop from the power supplied to the motor.

VFD motors are double insulated so that any nicks in the winding's insulation can be avoided. In order to withstand distorted power the winding's insulation has been enhanced for greater performance. The motors that remain susceptible to breakdown are those that were not changed when the drive was upgraded to an adjustable VFD type.

This cable is now left as the weakest link in the VFD system. If a motor power supply cable can be made so that it will not fail due to power distortions, the whole system will have been upgraded to handle the type of power that a VFD drive generates. The Lapp VFD cable exists which will insure trouble free operation even under the most extreme operating conditions.

VFD TESTING AND ANALYSIS

PdMA Corporation

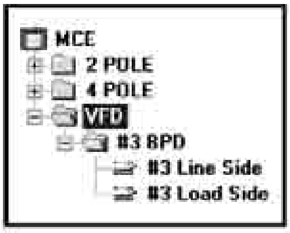
DESCRIPTION

Motors powered by variable frequency (VFD) or variable speed (VSD) drives require additional testing and analysis to ensure the high-voltage stresses are not weakening the motor's insulation system or the drive components. This application note is designed to give a quick review of the techniques for testing and analyzing VFDs and VFD driven motor data using the MCE-MAX.

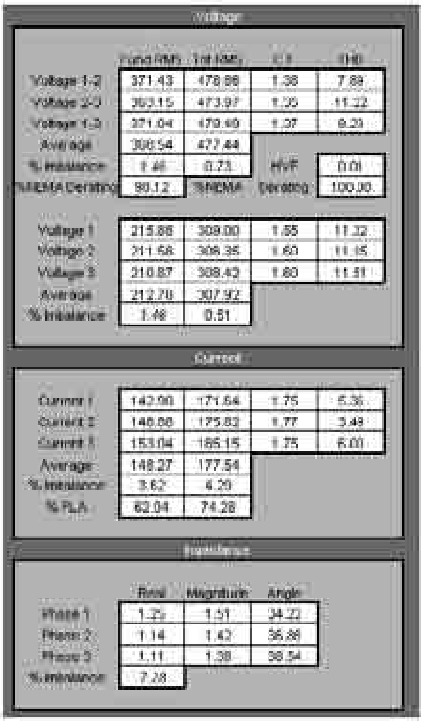
VFDs are made up of three components: the rectifier, storage, and inverter sections. Most VFD failures are the result of misapplication. Failures usually occur in the power sections, in either the rectifier or inverter.

PROCEDURE

- Establish two motors in the database for each drive motor combination. One will be used for EMAX testing on the line side of the VFD. The other will be used for MCE and EMAX testing on the load side of the VFD.



- Disconnect the VFD from the motor when performing MCE (deenergized) testing.
- Remove warning level set points which are not applicable to VFD signals. These include Current THD, HVF, FL, and Zimbalance for line side and VL-L, VTHD, HVF, and FL for load side.
- Refer to IEEE 519-1992 for standards on power quality.
- Perform the following tests:
  - Line Side Load Side
  - EMAX Power Analysis All MCE Tests
  - All EMAX Tests



Voltage

	Fund RMS	Tot RMS	CF	THD
Voltage 1-2	371.43	478.88	1.38	7.89
Voltage 2-3	363.15	473.97	1.35	11.22
Voltage 1-3	371.04	479.40	1.37	8.29
Average	368.54	477.44		
% Imbalance	1.46	0.73	HVF	0.01
%NEMA Derating	98.12	%NEMA	Derating	100.00

Voltage 1	215.88	309.00	1.55	11.22
Voltage 2	211.56	308.35	1.60	11.15
Voltage 3	210.87	308.42	1.60	11.51
Average	212.78	307.92		
% Imbalance	1.48	0.51		

Current

Current 1	142.90	171.64	1.75	5.36
Current 2	148.88	175.83	1.77	3.49
Current 3	153.04	185.15	1.75	6.00
Average	148.27	177.54		
% Imbalance	3.62	4.29		
% FLA	62.04	74.28		

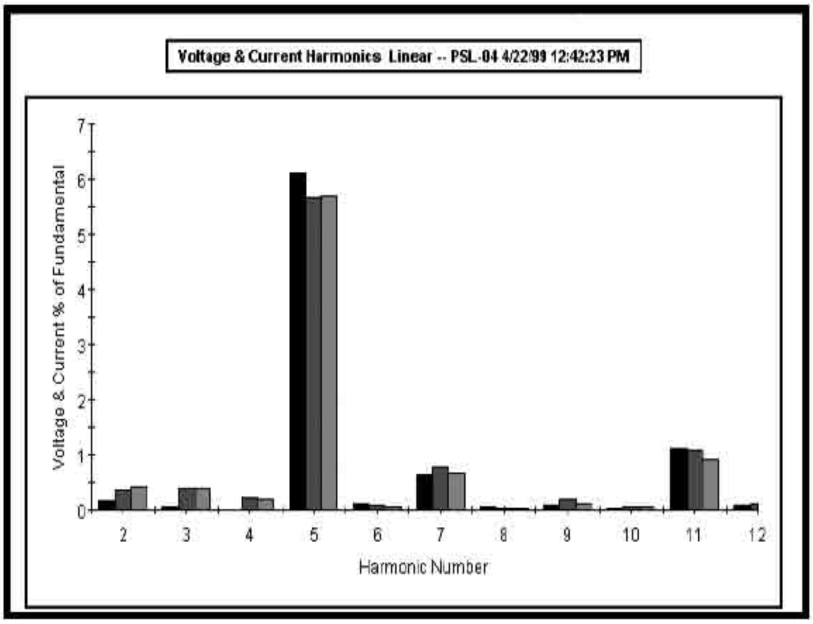
Impedance

	Real	Magnitude	Angle
Phase 1	1.25	1.51	34.22
Phase 2	1.14	1.42	36.88
Phase 3	1.11	1.38	38.54
% Imbalance	7.28		

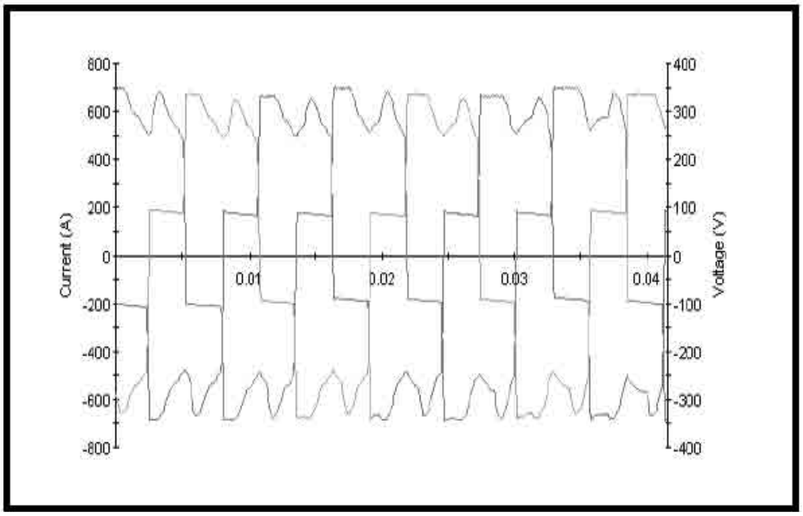
LINE SIDE ANALYSIS

Line Side Analysis focuses on the health of the VFD components, specifically the transistors.

- Monitor the voltage THD.
- Look for excessive harmonics of voltage on the voltage and current harmonics graph.
- High 5th and 7th harmonics indicate the presence of a 6 pulse drive influence on the distribution system. Each of the individual voltage harmonics should be <3% of the fundamental as per IEEE 519-1992. The figure shown below is an example of unacceptable levels of voltage distortion.



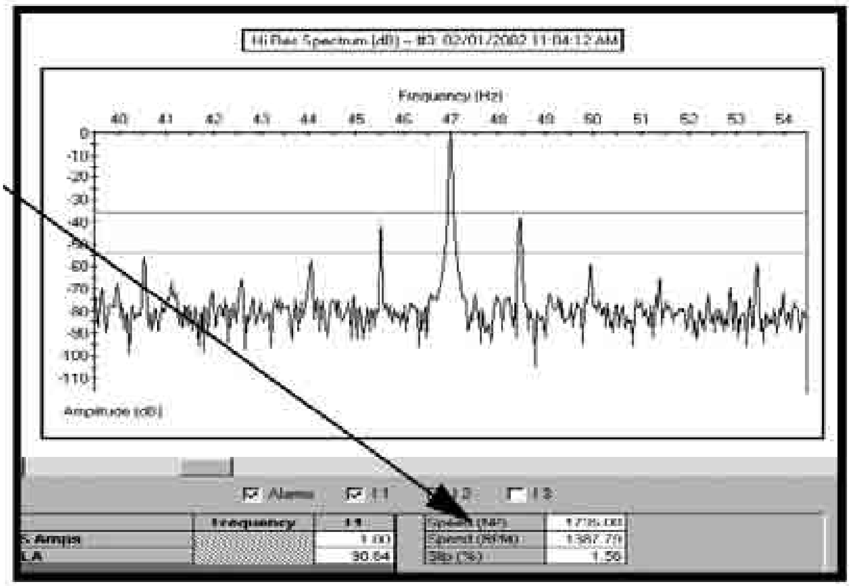
- IEEE 519-1992 is the Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems. It recommends for voltages greater than 600 VAC and less than 69k VAC, the overall voltage THD limit is 5%.
- Look for erratic zero crossings of voltage and current based on expected values and comparative values. The figure beside indicates a defective inverter section on the VFD.



LOAD SIDE ANALYSIS

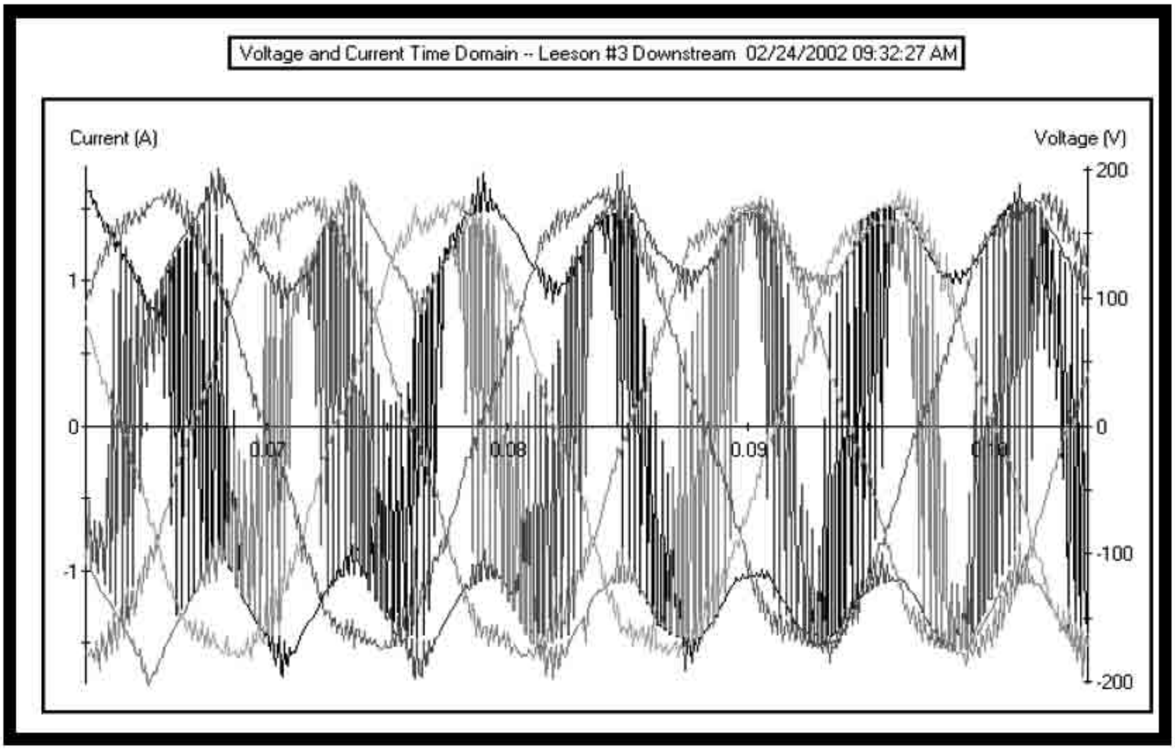
- IEEE 519-1992 power quality standards do not apply on the load side of a VFD.
- MCE testing analysis is identical for drive motors and non-drive motors.
- The voltage and current time domain is different, but still balanced, as shown beside.
- The EMAX Demod test for auto speed acquisition requires manual speed selection.
- EMAX Low Res, High Res, and Eccentricity tests have a built-in line frequency modifier so that the "Select Speed" and "Estimate Bars" algorithms are correct for different line frequencies.

Spectrum peak caution and alarm values are the same for drive motors and non-drive motors. Verify speed to confirm rotor defects.



	Frequency	I1
S Amps		1.00
LA		30.64

Speed (NP)	1775.00
Speed (RPM)	1387.79
Slip (%)	1.56


Voltage and Current Time Domain -- Leeson #3 Downstream 02/24/2002 09:32:27 AM
Current (A)
Voltage (V)
1
0
-1
200
100
0
-100
-200
0.07
0.08
0.09
0.10

SOLID STATE GIVES BETTER PROTECTION

Allen-Bradley

Electric motors fail for a number of reasons, including excessive heat, moisture and contamination; short circuits; mechanical problems; and simple old age!

The primary cause of motor failure is excessive heat, which is caused by:

- Excess current (current greater than the normal motor full load current)
- High ambient temperatures
- Poor ventilation of the motor.

In general, a single motor protective device alone cannot protect the motor from excessive heat due to all three of these causes. Currents greater than normal motor full load current can be caused by high inertia loads, such as loaded conveyors, locked rotor conditions, low voltage, phase failure and phase imbalance. If a motor is continuously overheated by only 10C°, its life can be reduced by as much as 50%.

All of these problems can be accounted for and measured to provide the very highest level of protection to the motor, so that the motor achieves the longest possible electrical and mechanical life in the application. Protecting motors against these various problems can be achieved with the functionality that electronics now provides in solid state motor protective devices.

By measuring parameters such as current, temperature and phase imbalance, damage to the motor's stator and rotor can be prevented, as well as providing an early warning that there may be trouble with another part of the mechanical system, such as conveyors, belts, gears and bearings.

There are significant differences in the construction and performance of electromechanical overload relays and solid state motor protective devices. They include the principles of operation of the two types of devices, the reduced heat dissipation and the energy savings that can be realised with solid state systems.

Traditional electromechanical overload relays (eutectic alloy or bimetallic) do not measure current directly. These devices operate by passing current through a heater element, which simulates the actual heating effect that is taking place in the motor. During overload conditions, the heat generated within the heater element reaches a level that causes a mechanism to operate and an auxiliary contact to open.

In typical installations, the contactor coil is wired in series with this contact. When the auxiliary contact opens, the contactor is de-energised, removing current from the motor.

Solid state motor protective devices, on the other hand, actually do measure current directly. Current can be measured in a variety of ways, but the most typical method of measuring current is using current transformers. Once an overload condition is reached, the electronic circuit of the motor protective device operates due to the increased level of current, causing a contact to open (similar to the electromechanical overload relay), de-energising the contactor and removing current from the motor.

Solid state electronics in motor protective devices not only provide traditional overload protection against the overcurrents that the motor is subjected to, but they also provide more information and protection against other fault conditions. These include: phase loss, phase imbalance, jam protection, ground fault (earth fault) protection, underload protection and over-temperature protection.

Under a phase loss condition, the motor current in the remaining two phases of a fully loaded motor increases to 1.73 times the normal motor full load current. A phase loss can occur due to a blown fuse or a poor electrical connection. With solid state electronics, in the motor protective device, the device can be designed so that it will trip, dropping out the starter within a 2 second period, thereby providing improved protection to the motor. Traditional electromechanical overload relays may take 40 seconds or longer after a phase loss, before the heat generated is sufficient to cause a trip.

Phase imbalances also cause an increase in current in the motor. A phase imbalance of only 5% requires a reduction in the permissible motor output of 25%, derating, for example, a 10HP motor to 7.5HP. Therefore, very small phase imbalances cannot be tolerated, because damage to the motor may occur, or the required output of the motor may not be achieved.

A high overload – or jam condition – can put unnecessary mechanical and thermal loading on the motor and the transmission elements. This might occur when a bearing seizes or parts are jammed in a conveyor. By sensing this jam current, the motor can be taken offline to prevent damage to components in the mechanical system. Jam protection is particularly useful in applications such as conveying systems, mills, mixers, crushers and saws.

Motors (for example, fans or submersible pumps) that are cooled by the medium being handled can become overheated in spite of being underloaded, due to the absence of sufficient medium. Causes might be clogged filters or closed valves. Often, such machines are installed in inaccessible places, making repair time consuming and expensive.

An underload, represented by the consumption of less than normal motor full load current, may indicate that there is a mechanical defect, such as a torn conveyor belt, damaged fan blades, broken shaft or worn tools. Such conditions may not harm the motor, but they do lead to loss of production or an interrupted production process. Rapid detection by the motor protective device helps to minimise both the damage and the downtime.

For increased safety of personnel in the area of motors and equipment, solid state motor protective devices can also provide ground fault protection. Ground faults in the motor occur when the insulation of the motor windings is damaged, perhaps by high voltage surges, age, sustained overloading or overheating, mechanical vibration or foreign objects, such as dust particles. In these instances, leakage to ground can occur. In grounded systems, the fault current can rise rapidly to a very high level, ultimately turning into a short circuit current. Solid state motor protective devices can sense ground fault currents before they rise to dangerous short circuit fault levels, and switch the motor offline before severe damage or severe injury to personnel occurs. Motor failure is most often caused by excessive heat. However, excessive heat is not only caused by increased incurrent, but it can also occur for other reasons, such as the ambient environment around the motor. Severe ambient conditions where there may not be sufficient ventilation to the motor, or where severe changes occur in the ambient temperature, would be applications where sensing current only would not be sufficient to protect the motor properly. In these types of applications, a temperature input from a positive temperature coefficient sensor or a resistance temperature detector (both of which are embedded in the motor windings) can be utilized to provide temperature input to the motor protective device. This additional information, utilized in conjunction with the motor current, will properly protect the motor, even when there may not be sufficient cooling.

REPLACING AN OVERSIZED AND UNDERLOADED ELECTRIC MOTOR

U.S. Department of Energy

This fact sheet will assist in decisions regarding replacement of oversized and underloaded motors. It includes a discussion of how the MotorMaster software can be used to conduct motor replacement analyses. Motors rarely operate at their full-load point. Field tests of 60 motors at four industrial plants indicate that, on average, they operate at 60% of their rated load. Motors that drive supply or return air fans in heating, ventilation and air-conditioning (HVAC) systems generally operate at 70% to 75% of rated load. A persistent myth is that oversized motors, especially motors operating below 50% of rated load, are not efficient and should be immediately replaced with appropriately sized energy-efficient units. In actuality, several pieces of information are required to complete an accurate assessment of energy savings. They are the load on the motor, the operating efficiency of the motor at that load point, the full-load speed (in revolutions per minute [rpm]) of the motor to be replaced, and the full-load speed of the downsized replacement motor.

MOTOR LOAD ESTIMATION TECHNIQUES

Operating efficiency and motor load values must be assumed or based on field measurements and motor nameplate information. The motor load is typically derived from a motor's part-load input kW measurements as compared to its full-load value (when kW or voltage, amperage, and power factor readings are available), from a voltage compensated amperage ratio, or from an operating speed to full-load slip relationship.

Equations used to estimate motor load are summarized on the folloiwng page. The kilowatt technique should be used whenever input kilowatt measurements are available. Use the slip technique only when strobe tachometer readings are at hand and kilowatt values are not available. The full-load or synchronous speed for the existing motor may be extracted from the nameplate, whereas speed characteristics for new motors are obtained from manufacturers' catalogs.

Motor Load Estimation Techniques

Kilowatt ratio technique

$$\text{Motor load} = \frac{\text{kW input or volts}_{\text{avg}} \times \text{amps}_{\text{avg}} \times (\text{power factor} / 100) \times \sqrt{3} / 1000}{(\text{hp rated} \times (.746) / \text{full load efficiency})}$$

voltage compensated slip technique

$$\text{Motor load} = \frac{\text{rpm}_{\text{synch}} - \text{rpm}_{\text{measured}}}{(\text{rpm}_{\text{synch}} - \text{rpm}_{\text{full load (nameplate)}}) \times \left[\dfrac{\text{rated voltage}}{\text{measured voltage}}\right]^2}$$

The Arizona Department of Commerce Energy Office has recommended against using the slip technique as an indicator of load and suggests that loads be estimated by comparing a motor's true root-mean-square (rms) amperage draw against its full-load or nameplate value. Thus, the load on a motor is defined as:

Amperage ratio technique

$$\text{Motor load} = \frac{\text{amps measured}}{\text{amps full load, nameplate}} \times \left[\frac{\text{volts measured}}{\text{volts nameplate}}\right]$$

While the amperage of a motor is approximately linear down to 50% load, the relationship is not directly proportional (i.e., at 50% load, current is higher than 50% of full-load current). An improved version of the amperage ratio load estimation technique makes use of a linear interpolation between a motor's full- and half-load current values. The modified equation, useful for estimating loads in the 50% to full-load range, is:

$$\text{Motor Load} = 0.5 + 0.5 \times \left[\frac{\text{amps}_{\text{measured}} \times \left[\dfrac{\text{volts measured}}{\text{volts nameplate}}\right] - \text{amps}_{50\%\ \text{load}}}{\text{amps}_{\text{full load}} - \text{amps}_{50\%\ \text{load}}}\right]$$

The current at 50% load (amps50%) can be found from manufacturer data or MotorMaster. The accuracy of the amperage ratio methodology is best for motors with outputs exceeding 10 shaft horsepower (hp). Below 50% load, the amperage curve becomes increasingly nonlinear and is therefore not a good indicator of load. Amperage draws at 50% load for motors of different sizes and speeds are given in Figure 1. This figure can be used to approximate current values when specific motor data are not available.

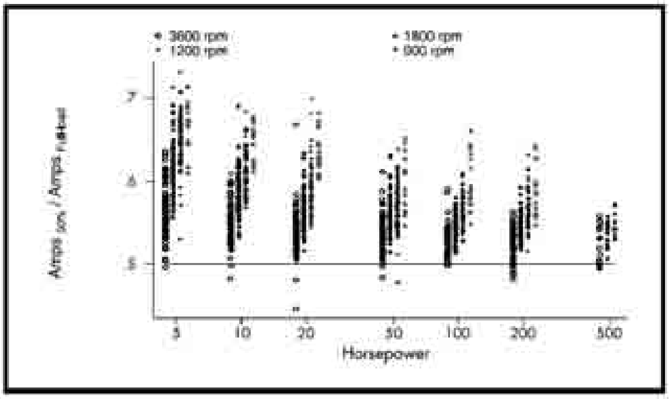


Figure 1

EFFICIENCY VERSUS MOTOR LOAD RELATIONSHIPS

The efficiency of both standard and energy-efficient motors typically peaks near 75% of full load and is relatively flat down to the 50% load point. Motors in the larger size ranges can operate with reasonably high efficiency at loads down to 25% of rated load. Efficiency values at partial load points are given in Table 1 for energy-efficient and standard motor models of various sizes.

An inspection of Table 1 indicates two additional trends: (1) larger motors exhibit both higher full- and partial-load efficiency values, and (2) the efficiency decline below the 50% load point occurs more rapidly for the smaller size motors. Thus, a 100-hp standard motor operating at 40% of rated load may operate as efficiently as an energy efficient 40-hp motor operating at its rated load point. On the other hand, an energy-efficient 5-hp replacement motor could operate with an efficiency as much as five points above that of a standard 10-hp motor operating at its 40% load point.

Table 1
Efficiency at Full and Partial Loads for 1800 RPM, ODP Motors

	Full Load	75% Load	50% Load	25% Load
100 hp				
U.S. Motors - Premium	95.8	96.1	96.1	94.3
Reliance XE	95.4	95.7	95.4	93.2
Magnetek Standard	93.0	94.0	94.0	89.3
U.S. Motors – Standard	92.4	93.8	93.9	91.6
40 hp				
U.S. Motors – Premium	94.5	94.9	94.6	92.0
Reliance XE	94.1	94.1	94.0	91.4
Magnetek Standard	91.0	89.5	92.4	86.5
U.S. Motors – Standard	90.2	88.0	90.8	86.9
20 hp				
U.S. Motors – Premium	93.0	92.7	92.5	89.5
Reliance XE	92.0	93.0	92.0	84.8
Magnetek Standard	88.5	89.5	89.5	84.0
U.S. Motors – Standard	88.0	88.0	86.3	79.9
10 hp				
U.S. Motors – Premium	91.7	90.4	89.8	85.3
Reliance XE	91.7	92.2	91.8	87.8
Magnetek Standard	87.7	89.5	88.5	82.5
U.S. Motors – Standard	86.0	88.0	86.0	80.6
5 hp				
U.S. Motors – Premium	89.5	90.4	89.5	84.3
Reliance XE	89.5	89.7	87.5	82.6
Magnetek Standard	85.5	86.5	85.5	75.0
U.S. Motors – Standard	84.0	84.0	82.0	74.0

Source: MotorMaster database

MOTOR LOAD AND SPEED RELATIONSHIPS

The actual operating speed of an induction motor is somewhat less than its synchronous speed. This difference between the synchronous and actual speed is referred to as slip. Many energy-efficient motors tend to operate with a reduced full-load slip or at a slightly higher speed than their standard efficiency counterparts. This small difference can be significant. For centrifugal fans and pumps, even a minor change in the motor's operating speed translates into a significant change in imposed load and annual energy consumption. Fan and pump "affinity" laws indicate that the horsepower loading placed upon a motor by centrifugal loads varies as the third power or cube of its rotational speed. A seemingly minor 20 rpm increase in a motor's rotational speed – from 1740 to 1760 rpm – can result in a 3.5% increase in the load placed upon a motor driving a pump or fan. In contrast, the quantity of air or water delivered varies linearly with speed.

Slip and operating speed are dependent upon applied load, and the loading imposed upon a motor is, in turn, dependent upon its size. For example, a 25% loaded 100-hp motor could be replaced by a 50-hp motor loaded to approximately 50%; a 62.5% loaded 40-hp motor; an 83% loaded 30-hp motor; or a fully loaded 25-hp motor.

As loads on a motor are progressively increased, it begins to rotate slower until, at the full-load point, operation occurs at the full-load speed. Thus, oversized and lightly loaded motors tend to operate at speeds which approach synchronous. An appropriately sized smaller or fully loaded energy-efficient motor, with a higher full-load rpm than the motor to be replaced, may actually operate at a slower speed than the original oversized motor.

This speed and load shift can be significant and must be taken into account when computing both energy and demand savings. For example, consider a 40% loaded, four-pole, 10-hp Siemens ODP standard efficiency motor which is to be replaced by a 5-hp, energy-efficient, U.S. Motors premium efficiency unit or a Magnetek E-Plus 3 motor.

The Siemens motor has a full-load efficiency of 84.0% at a full-load speed of 1720 rpm. The U.S. Motors and Magnetek products both exhibit full-load efficiencies of 89.5% with full-load speeds of 1760 and 1740 rpm, respectively.

The Siemens motor would actually operate at 1768 rpm. The U.S. Motors energy-efficient motor would also rotate at 1768 rpm, while the Magnetek unit would turn at 1753 rpm. Energy savings, assuming 2500 hours per year of operation, are 849 kilowatt-hours (kWh) for the U.S. Motors unit and 1010 kWh for the Magnetek machine. While operating at this reduced speed, the Magnetek unit would provide about 1% less air or water flow. Energy savings and load points for the U.S. Motors and Magnetek motor are given in Table 2, assuming that the full-load speed for the oversized 10-hp motor ranges from 1715 to 1760 rpm.

Note that, if motor operating speed is ignored, the annual savings given replacement with the 1740 rpm Magnetek motor is 803 kWh. The energy savings could increase to 1209 kWh if the replaced oversized motor happened to have a full-load speed of 1760 rpm. This very real possibility would result in a savings increase of 406 kWh, approximately 50% greater than that predicted if speed correction factors are neglected.

Table 2
Energy Savings Due to Replacement of an Oversized Motor as a Function of Full-Load Speed

Full-Load rpm of Oversized Motor	Load Imposed on 5-hp 1780 rpm Motor, % of Rated	Annual Energy Savings, kWh*
1715	80.26	823
1720	80.00	849
1730	79.49	902
1740	78.98	955
1750	78.47	1007
1760	77.97	1059
No speed correction: 849 kWh		
Full-Load rpm of Oversized Motor	**Load Imposed on 5-hp 1740 rpm Motor, % of Rated**	**Annual Energy Savings, kWh***
1715	78.25	985
1720	78.01	1010
1730	77.52	1061
1740	77.03	1111
1750	76.55	1161
1760	76.08	1209
No speed correction: 803 kWh		

* Assumes replacement of a standard-efficiency 10-hp, 40% loaded motor with an energy-efficient 1800 rpm 5-hp unit with 2500 hours per year of operation.

A final word of caution is needed. The National Electrical Manufacturers Association does not require high precision for the nameplate full-load rpm value. An error of plus or minus 20% in slip is allowed. This can represent Å}10 rpm for both the existing and replacement 1800 rpm motors. A significant uncertainty is introduced. Greater deviation in full-load rpm can occur if the existing motor has been rewound.

USING MOTORMASTER TO CONDUCT ANALYSES OF OVERSIZED MOTOR REPLACEMENT OPPORTUNITIES

MotorMaster software contains a speed/correction algorithm such that when the nameplate full-load speed of the motor to be replaced is entered, the increase or decrease in load for the replacement motor is automatically calculated. Speed change effects are thus used to determine annual energy and dollar savings and the simple payback from investing in a new, energy-efficient motor.

MotorMaster also contains full, 75%, 50%, and 25% load and power factor data for most motors. An oversized motor replacement analysis can readily be made, with MotorMaster interpolating to determine the efficiency at the appropriate internally computed load point for the new downsized motor. Equipment and installation cost data for the replacement motor are automatically entered into the analysis and speed correction is again automatically accounted for. MotorMaster's Compare Section was specifically created to effectively and correctly conduct analyses of oversized and underloaded motors.

In addition, a Windows-based enhancement to MotorMaster, called MotorMaster+, is available. MotorMaster+ not only facilitates the selection of energy-efficient motors, but can also assist energy coordinators in implementing an effective energy management program. MotorMaster+ has many tools to support energy management activities. These tools include a motor inventory model, a field measurement and operating data storage repository, descriptor search and selective report-writing capability, internal motor load and efficiency estimation capability, MotorMaster database interface, and life-cycle costing analysis. If you are interested in communicating electronically with other motor system professionals, review the motor-related forums on the Motor Challenge website.

The Motor Challenge website can be accessed at http://www.motor.doe.gov.

REFERENCES

Kueck, J. D; Gray, J. R.; Driver, R. C.; and Hsu, J. S. Assessment of Available Methods for Evaluating In-Service Motor Efficiency. Oak Ridge National Laboratory, ORNL-TM-13237. April 1996.

McCoy, G. A; Douglass, J. G. Energy Efficient Electric Motor Selection Handbook. U.S. Department of Energy and Bonneville Power Administration, DOE/GO-10096-290. Reprint August 1996.

Nailen, R. L. "Finding True Power Output Isn't Easy." Electrical Apparatus. February 1994.

POWER SYSTEM HARMONICS

Causes and Effects of Variable Frequency Drives Relative to the IEEE 519-1992 Standard

Square D

INTRODUCTION

This document describes power system harmonics as they relate to AC variable frequency drives controlling centrifugal pumping applications. Some of the topics covered are:

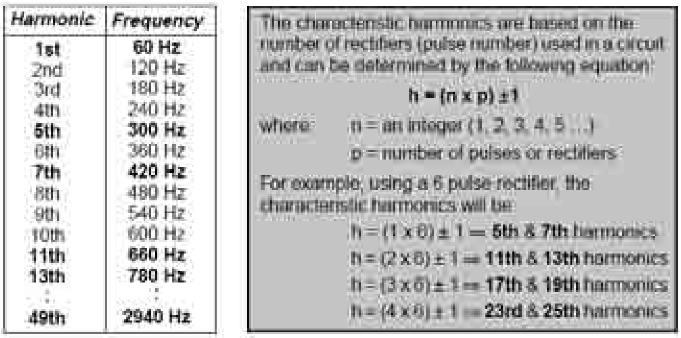
- Definition of harmonics
- How AC variable frequency drives create harmonics
- Effects of variable frequency drives on the AC line
- Three-phase harmonics associated with phase-to-phase loads
- Controlling harmonics

Information on the IEEE 519-1992 standard can be found in "IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems". The issues and considerations associated with three-phase power harmonics are often misunderstood. With the advent of power electronics and proliferation of non-linear loads in industrial power applications, power harmonics and their effects on power quality are a topic of concern. Currently in the United States, only 15 to 20% of the utility distribution loading consists of non-linear loads. It is projected that over the next ten years non-linear loads will comprise approximately 70 to 85% of the loading on the nation's utility distribution systems.

The effects of single-phase power harmonics and neutral conductors are often a source of concern. Harmonics play an important role in single-phase applications if the neutral conductors are undersized, however single-phase harmonics are associated with phase-to-neutral loads and are not discussed in this document.

HARMONICS

A harmonic is a component of a periodic wave having a frequency that is an integral multiple of the fundamental power line frequency of 60 Hz. Harmonics are the multiple of the fundamental frequency, as shown in Figure 1. Total harmonic distortion is the contribution of all the harmonic frequency currents to the fundamental.



Harmonic	*Frequency*
1st	**60 Hz**
2nd	120 Hz
3rd	180 Hz
4th	240 Hz
5th	**300 Hz**
6th	360 Hz
7th	**420 Hz**
8th	480 Hz
9th	540 Hz
10th	600 Hz
11th	**660 Hz**
13th	**780 Hz**
⋮	⋮
49th	**2940 Hz**

The characteristic harmonics are based on the number of rectifiers (pulse number) used in a circuit and can be determined by the following equation:

$$h = (n \times p) \pm 1$$

where: n = an integer (1, 2, 3, 4, 5 ...)
p = number of pulses or rectifiers

For example, using a 6 pulse rectifier, the characteristic harmonics will be:

$h = (1 \times 6) \pm 1 =$ **5th & 7th** harmonics
$h = (2 \times 6) \pm 1 =$ **11th & 13th** hormonics
$h = (3 \times 6) \pm 1 =$ **17th & 19th** harmonics
$h = (4 \times 6) \pm 1 =$ **23rd & 25th** harmonics

Figure 1. Determining Characteristic Harmonics

HOW HARMONICS ARE PRODUCED

Harmonics are the by-products of modern electronics. They occur frequently when there are large numbers of personal computers (single-phase loads), uninterruptible power supplies (UPSs), variable frequency drives (AC and DC) or any electronic device using solid state power switching supplies to convert incoming AC to DC.

Non-linear loads create harmonics by drawing current in abrupt short pulses, rather than in a smooth sinusoidal manner (see Figure 2). The terms "linear" and "non-linear" define the relationship of current to the voltage waveform. A linear relationship exists between the voltage and current, which is typical of an across-the-line load. A non-linear load has a discontinuous current relationship that does not correspond to the applied voltage waveform.

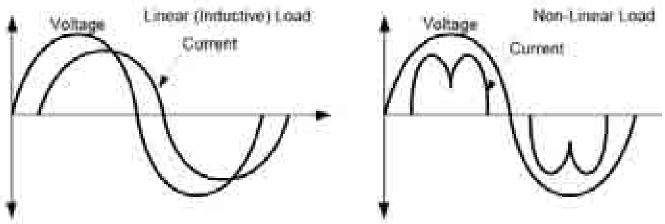


Figure 2. Differences between Linear and Non-Linear Loads

HOW VARIABLE FREQUENCY DRIVES CAUSE HARMONICS

All variable frequency drives cause harmonics because of the nature of the front end rectifier design. Figure 3 illustrates the typical 6-pulse rectifier. This is the standard power circuit elementary configuration for most pulse width modulated variable frequency drives with diode bridge rectifiers sold in the marketplace today.

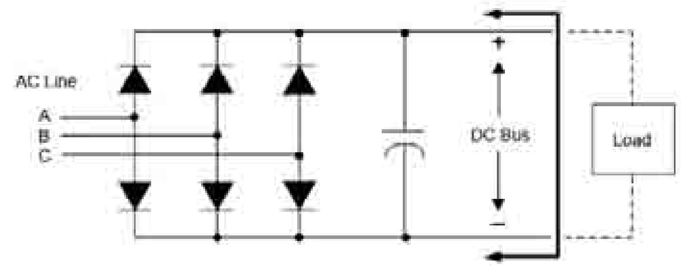


Figure 3. Typical Six-Pulse Front End Converter for AC Drive

Some manufacturers offer an alternative design, particularly in large horsepower configurations, that incorporates the advantages of a 12-pulse configuration. The 12-pulse configuration still creates harmonics to some degree by eliminating the 5th and

7th harmonics and extending the primary characteristic harmonics up to the 11th and 13th.

Capacitors charge by drawing current instantaneously and charging to a rated voltage potential. Figure 3 shows the relationship of voltage and current with respect to time for a typical capacitor from the moment power is applied.

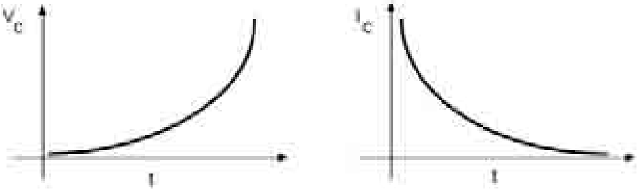


Figure 4. Capacitor Voltage and Current Relationships

After one half cycle, the DC bus capacitors are charged to the peak of the AC voltage sine wave. The connected motor draws current from the DC bus (high DC voltage) to supply power to the load requirements.

Three-phase harmonics occur when incoming AC voltage is rectified by the three-phase full wave diode bridge, which charges the capacitor banks in the DC bus. The conversion from AC to DC is used to charge the capacitors to a rated potential.

As the motor draws the voltage from the DC bus supply, the potential on the capacitors is less than the incoming line voltage. Before reaching a lower regulated limit, the DC bus capacitors recharge again in the next half cycle of the voltage sine wave to the peak. This process is repeated twice in each peak of the sine wave from the process of continuously charging and discharging of the DC bus capacitors. The capacitors draw a pulse of current (non-linear load) only during the first and second half peak of the voltage sine wave.

The degree and magnitude of the harmonics created by the variable frequency drive is a function of the drive design and the inter-relationship of the non-linear load with the connected distribution system impedance. The power source line impedance ahead of the controller will determine the magnitude and amplitude of harmonic currents and voltages reflected back into the distribution system. Figure 5 illustrates this relationship.

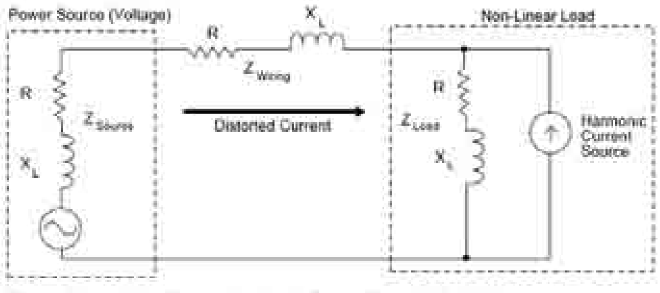


Figure 5. Non-Linear Load and Power Supply Modeling

The distorted current reflected through the distribution impedance causes a voltage drop or harmonic voltage distortion. This relationship is proportional to the distribution system available fault current and to the industrial distribution system impedance design.

- High fault current (stiff system)
  - Distribution system impedance and distortion is low
  - Harmonic current draw is high
- Low fault current (soft system)
  - Distribution system impedance and distortion is high
  - Harmonic current draw is low

EFFECTS AND NEGATIVE CONSEQUENCES

The effects of three-phase harmonics on circuits are similar to the effects of stress and high blood pressure on the human body. High levels of stress or harmonic distortion can lead to problems for the utility's distribution system, plant distribution system and any other equipment serviced by that distribution system. Effects can range from spurious operation of equipment to a shutdown of important plant equipment, such as machines or assembly lines.

Harmonics can lead to power system inefficiency. Some of the negative ways that harmonics may affect plant equipment are listed below:

Conductor Overheating:

A function of the square rms current per unit volume of the conductor. Harmonic currents on undersized conductors or cables can cause a "skin effect", which increases with frequency and is similar to a centrifugal force.

Capacitors:

Can be affected by heat rise increases due to power loss and reduced life on the capacitors. If a capacitor is tuned to one of the characteristic harmonics such as the 5th or 7th, over voltage and resonance can cause dielectric failure or rupture the capacitor.

Fuses and Circuit Breakers:

Harmonics can cause false or spurious operations and trips, damaging or blowing components for no apparent reason.

Transformers:

Have increased iron and copper losses or eddy currents due to stray flux losses. This causes excessive overheating in the transformer windings. Typically, the use of appropriate "K factor" rated units are recommended for non-linear loads.

Generators:

Have similar problems to transformers. Sizing and coordination is critical to the operation of the voltage regulator and controls. Excessive harmonic voltage distortion will cause multiple zero crossings of the current waveform. Multiple zero crossings affect the timing of the voltage regulator, causing interference and operation instability.

Utility Meters:

May record measurements incorrectly, result in higher billings to consumers.

Drives/Power Supplies:

Can be affected by misoperation due to multiple zero crossings. Harmonics can cause failure of the commutation circuits, found in DC drives and AC drives with silicon controlled rectifiers (SCRs).

Computers/Telephones:

May experience interference or failures.

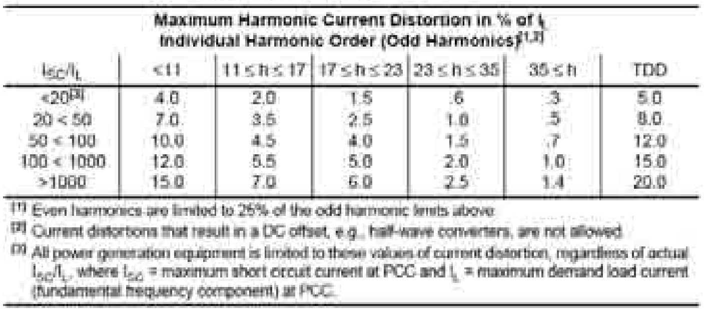
IEEE 519-1992 GUIDELINES

IEEE 519-1981, *"IEEE Guide for Harmonic Control and Reactive Compensation of Static Power Converters"*, originally established levels of voltage distortion acceptable to the distribution system for individual non-linear loads. With the rising increase usage of industrial non-linear loads, such as variable frequency drives, it became necessary to revise the standard.

The IEEE working groups of the Power Engineering Society and the Industrial Applications Society prepared recommended guidelines for power quality that the utility must supply and the industrial user can inject back onto the power distribution system. The revised standard was issued on April 12, 1993 and titled *"IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems"*

The revisions to IEEE 519-1992 establish recommended guidelines for harmonic voltages on the utility distribution system as well as harmonic currents within the industrial distribution system. According to the standard, the industrial system is responsible for controlling the harmonic currents created in the industrial workplace. Since harmonic currents reflected through distribution system impedances generate harmonic voltages on the utility distribution systems, the standard proposes guidelines based on industrial distribution system design. Table 10.3 from IEEE 519-1992 defines levels of harmonic currents that an industrial user can inject onto the utility distribution system.

IEEE Table 10.3 Current Distortion Limits for General Distribution Systems (120 V through 69 kV)



	Maximum Harmonic Current Distortion in % of I_L Individual Harmonic Order (Odd Harmonics)[1,2]					
I_{SC}/I_L	<11	$11 \le h \le 17$	$17 \le h \le 23$	$23 \le h \le 35$	$35 \le h$	TDD
<20[3]	4.0	2.0	1.5	.6	.3	5.0
20 < 50	7.0	3.5	2.5	1.0	.5	8.0
50 < 100	10.0	4.5	4.0	1.5	.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

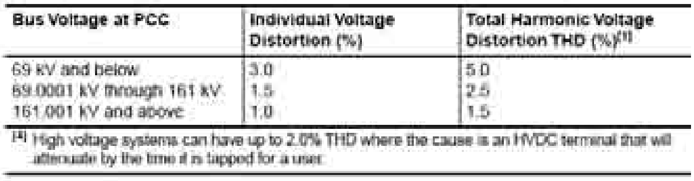
[1] Even harmonics are limited to 25% of the odd harmonic limits above

[2] Current distortions that result in a DC offset, e.g., half-wave converters, are not allowed

[3] All power generation equipment is limited to these values of current distortion, regardless of actual I_{SC}/I_L, where I_{SC} = maximum short circuit current at PCC and I_L = maximum demand load current (fundamental frequency component) at PCC

Table 11.1 of IEEE 519-1992 defines the voltage distortion limits that can be re-flected back onto the utility distribution system. Usually if the industrial user controls the overall combined current distortion according to Table 10.3, this will help them meet the limitations set forth in the guidelines.

IEEE Table 11.1 Voltage Distortion Limits



Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Harmonic Voltage Distortion THD (%)[1]
69 kV and below	3.0	5.0
69.0001 kV through 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5

[1] High voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user

Some important concepts and terms associated with a harmonic analysis involve PCC, TDD and THD. The Point of Common Coupling (PCC) is the location of the harmonic voltage and current distortion to be calculated or measured. PCC can be measured or calculated on the primary or secondary of a utility transformer or at the service entrance of the facility. In some cases, PCC can be measured or calculated between the non-linear loads and other loads of an industrial plant. Total Demand Distortion (TDD) is the percentage of total harmonic current distortion calculated or measured at PCC. Total Harmonic Distortion (THD) is the total harmonic voltage distortion calculated or measured at PCC.

A task force was created to develop an application guide for IEEE 519 to help users and utilities in cooperate and understand how to solve potential problems related to power system harmonics.

EVALUATING SYSTEM HARMONICS

In order to prevent or correct harmonic problems that could occur within an industrial facility, an evaluation of system harmonics should be performed if the facility conditions meet one or more of the criteria below.

- The application of capacitor banks in systems where 20% or more of the load includes other harmonic generating equipment.
- The facility has a history of harmonic related problems, including excessive capacitor fuse operation.
- During the design stage of a facility composed of capacitor banks and harmonic generating equipment.
- In facilities where restrictive power company requirements limit the harmonic injection back into their system to very small magnitudes.
- Plant expansions that add significant harmonic generating equipment operating in conjunction with capacitor banks.
- When coordinating and planning to add an emergency standby generator as an alternate power source in an industrial facility.

Often, the vendor or supplier of non-linear load equipment, such as variable frequency drives, can evaluate the effects that the equipment may have on the distribution system. This usually involves details related to the distribution system design and impedances, similar to performing a short circuit study evaluation.

REDUCING HARMONICS

There are many ways to reduce harmonics, ranging from variable frequency drive designs to the addition of auxiliary equipment. The primary methods used today to reduce harmonics are:

Power System Design:

Harmonics can be reduced by limiting the non-linear load to 30% of the maximum transformer's capacity. However, with power factor correction capacitors installed, resonating conditions can occur that could potentially limit the percentage of non-linear loads to 15% of the transformer's capacity. Use the following equation to determine if a resonant condition on the distribution could occur:

$$hr = \sqrt{\frac{kVAsc}{kVARc}}$$

where…

h_r = resonant frequency as a multiple of the fundamental frequency

kVA_{SC} = short circuit current at the point of study

$kVAR_C$ = capacitor rating at the system voltage

If hr equals or is closed to a characteristic harmonic, such as the 5th or 7th, there is a possibility that a resonant condition could occur.

12-pulse converter front end:

In this configuration, the front end of the bridge rectifier circuit uses twelve diodes instead of six. The advantages are the elimination of the 5th and 7th harmonics to a higher order where the 11th and 13th become the predominate harmonics. This will minimize the magnitude of harmonics, but will not eliminate them. The disadvantages are cost and construction, which also requires either a Delta-Delta and Delta-Wye transformer, "Zig-Zag" transformer or an autotransformer to accomplish the 30∞ phase shifting necessary for proper operation. This configuration also affects the overall drive system efficiency rating because of the voltage drop associated with the transformer configuration requirement. Figure 6 illustrates the typical elementary diagram for a 12-pulse converter front end.

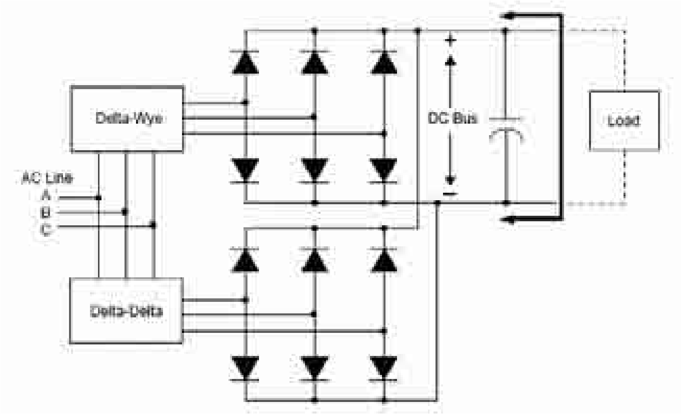


Figure 6. Typical Twelve-Pulse Front End Converter for AC Drive

Delta-Delta and Delta-Wye Transformers:

This configuration uses two separate utility feed transformers with equal non-linear loads. This shifts the phase relationship to various six-pulse converters through cancellation techniques, similar to the twelve-pulse configuration.

Isolation Transformers:

An isolation transformer provides a good solution in many cases. The advantage is the potential to "voltage match" by stepping up or stepping down the system voltage, and by providing a neutral ground reference for nuisance ground faults. This is the best solution when utilizing AC or DC drives that use SCRs as bridge rectifiers.

Line Reactors:

More commonly used for size and cost, the line reactor is the best solution for harmonic reduction when compared to an isolation transformer. AC drives that use diode bridge rectifier front ends are best suited for line reactors. Line reactors (commonly referred to as inductors) are available in standard impedance ranges from 1.5%, 3%, 5% and 7.5%.

Harmonic Trap Filters:

Used in applications with a high non-linear ratio to system to eliminate harmonic currents. Filters are tuned to a specific harmonic such as the 5th, 7th, 11th, etc. In addition, harmonic trap filters provide true distortion power factor correction. Filters can be designed for several non-linear loads or for an individual load, as shown in Figure 7.

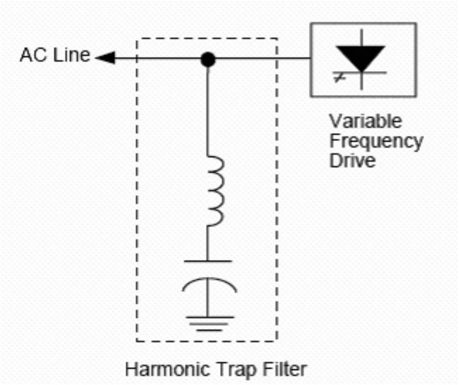


Figure 7. Typical Harmonic Trap Filter Configuration

SUMMARY

With the proliferation of non-linear loads, the issues of power harmonics are more apparent than ever. Controlling and monitoring industrial system designs and their effects on utility distribution systems are a potential problem for the industrial consumer who is responsible for complying with the IEEE 519-1992 recommended practices and procedures. Industrial facilities should include a system evaluation, including a harmonic distortion analysis, while planning facility construction or expansion. Vendors of non-linear loads such as variable frequency drives can provide services and recommend equipment that will reduce harmonics in order to comply with the revised IEEE 519-1992 guidelines.

REFERENCES

1. Murphy and F.G. Turnbull, "Power Electronic Control of AC Motors", Pergamon Press, Elmsford, New York, 1988.
2. Industrial and Commercial Power Systems Analysis, ANSI/IEEE Std. 399-1990, Chapter 10.
3. Electric Power Distribution for Industrial Plants, ANSI/IEEE Std. 141-1986, Chapter 8.
4. IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems, ANSI/IEEE Std. 519-1992.
5. John F. Hibbard and Michael Z. Lowenstein, "Meeting IEEE 519-1992 Harmonic Limits", TCI (Trans Coil, Inc.), 1993
6. "In Tune with Power Harmonics", John Fluke Mfg. Co., Inc., 1991
7. Ed Palko, "Living with Power System Harmonics", Plant Engineering, June 18, 1992, pages 48-53.
8. "Harmonic Filtering – A Guide for the Plant Engineer", Commonwealth Sprague Capacitor, Inc., 1991.

ADJUSTABLE FREQUENCY DRIVES AND HVAC SYSTEMS

An Application Guide

Square D

INTRODUCTION

All buildings pose the same problem: how to heat or cool the air inside to create a more comfortable environment for the occupants. In small buildings such as a house, this task is easily handled with air conditioners and heaters. Larger buildings such as offices, hotels, or factories pose a more difficult problem due to their size and complexity.

The most typical heating and cooling solution is to move air around the building while modifying the air temperature by passing the air over heated or cooled water as required. Such a system consists of a water stage and an air stage. Figure 1 illustrates the basic concept of such a system.

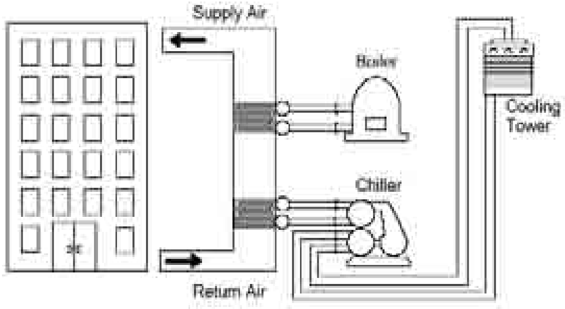


Figure 1. Heating, Ventilation, and Air Conditioning (HVAC) System

WATER STAGE

The water stage is the first step of temperature control. Air is not an efficient medium to heat or cool directly. The most efficient and inexpensive medium that we can heat or cool is water. This water can then be used to change the temperature of the passing air.

Heating water is very simple. Municipally-supplied water is pumped into a boiler where it is exposed to heat from oil, gas, coal, or electricity. The hot water is then pumped out into coils that are used for heating the building air. Cooling water is a little more complex and revolves around a device called a chiller. A chiller consists of a compressor, a condenser, and an evaporator. Two separate water circuits exist in the chiller; one circuit removing heat from the building air and one circuit dissipating that heat via a cooling tower.

AIR STAGE

The air stage is the medium for heat exchange in the building spaces. Air is constantly circulated through a building to either bring in or carry away heat as required. If the air needs to be cooled, it is directed over coils of cool water. If the air needs to be heated, it flows over coils of hot water. Outside air is also vented in at times to save chiller energy when the outside air temperature is cool enough to help the system.

HVAC SYSTEM ARCHITECTURE

Every building, when designed, presents a different type of heating and cooling challenge. Correspondingly, a wide range of HVAC solutions have been developed over the years, particularly for large buildings.

SINGLE ZONE SYSTEM

The most simple and common of all HVAC designs is the single duct/single zone system, much like the system shown in Figure 2. This system is designed to supply air at a single temperature to a single large area (or zone) of a building. Some buildings are designed with the entire structure as a single zone. Although this system is simple and inexpensive to construct, the lack of control makes it difficult to keep all of the occupants comfortable, especially if parts of the building are affected differently by wind or sunlight. This type of system also wastes energy when heating or cooling areas that do not require it.

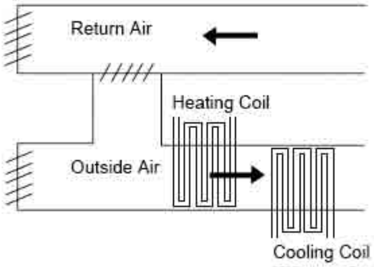


Figure 2. Single-Zone System

The most flexible part of a single zone system is the selectable recirculation of building air. Selectable air recirculation is common to most HVAC architectures and is part of all the systems discussed here. In this design, outside air is only used if its temperature will move the building temperature in the desired direction, warmer or colder. If the outside air is not at a useful temperature, the outside air dampers may be closed and the intermix damper opened to allow the building air to recirculate. However, the outside air dampers do not close all the way. Some outside air must be brought in for health reasons. It is a general requirement that 20 cubic feet per minute of air be brought in for each occupant at all times.

TERMINAL RE-HEAT SYSTEM

A slightly more sophisticated system is called terminal reheat (see Figure 3). These systems send out uniformly cool or hot air to multiple zones in a building. Each zone is equipped with a thermostat and a heating coil. When a zone's thermostat calls for warmer air, a heating coil is activated to provide the required heat.

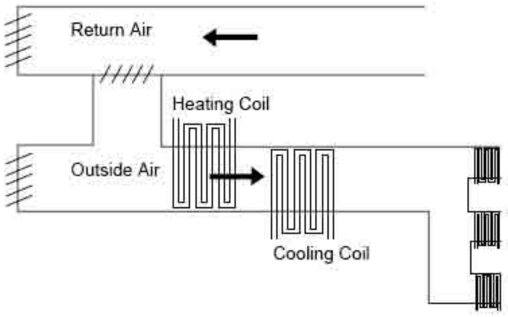


Figure 3. Terminal Reheat System

HOT DECK/COLD DECK SYSTEM

Many large zone systems use air directed over cooling coils in one duct as cool air, and air directed over heating coils in another duct as hot air for ventilation. These sections are usually referred to as the hot deck and the cold deck. As in the previous cases, this system makes use of outside air when appropriate. Figure 4 shows the typical configuration for such a system. This approach is also used for multiple zone systems. By paralleling several of the systems shown, from common outside air ducts, hot and cold deck systems can operate independently for each zone.

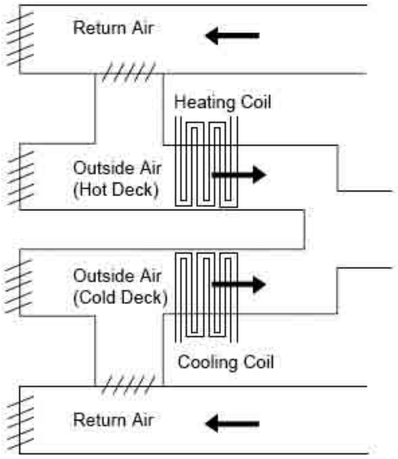


Figure 4. Hot Deck/Cold Deck System

DUAL DUCT SYSTEM

More cooling efficiency can be gained by using dual duct systems (see Figure 5). In a dual duct system, the hot and cold deck air is brought to each building zone independently. Each zone has a thermostat-controlled mixing box. This box feeds the proper combination of hot and cold air to reach the thermostat's set point for the zone.

In better systems, a control scheme detects periods where no zones are calling for either hot or cold air and shuts down the appropriate system. In the morning, for example, it is unlikely that cold air will be required as the building heats up. In that instance, the cold deck coil and fan would be shut down to conserve energy.

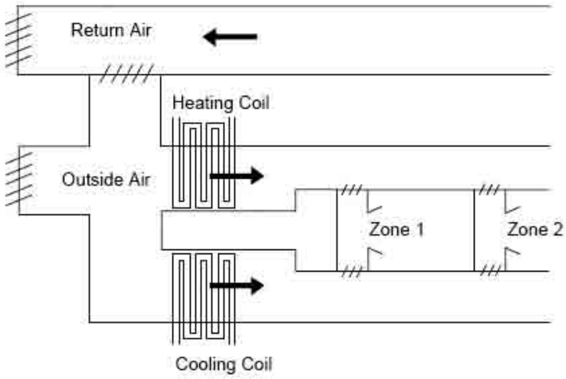


Figure 5. Dual Duct System

VAV SYSTEMS

The most sophisticated systems are variable air volume (VAV) systems, as shown in Figure 6. In VAV systems, a central unit supplies cooled or heated air at constant, controllable temperatures to VAV boxes for each zone. By opening and closing vanes in the airflow, these boxes vary the quantity rather than the temperature of the air, resulting in the desired amount of cooling or heating in the zone. In structures where zoned air conditioning is required, VAV is the most common choice. VAV is also the most energy efficient of the mechanical control systems. A static pressure sensor in the main duct detects changes in the duct pressure caused by the opening and closing of the zone boxes. This pressure reading is used in a loop control scheme with vanes or dampers on the supply fan to maintain a constant static pressure in the duct. When less air is required to maintain the pressure (i.e., the zone boxes are closed), the fan is unloaded and consumes less energy.

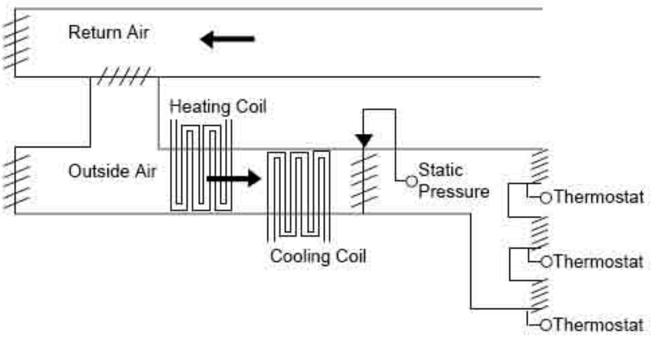


Figure 6. VAV System

COOLING SYSTEMS

Providing cooling is the most complex part of HVAC systems. The two primary components used to achieve this are chillers and cooling towers.

CHILLERS

A chiller is the central means of heat exchange between the inside and outside of a building (refer to Figure 7). The chiller serves two basic functions: to cool the air in a building and to provide dehumidification.

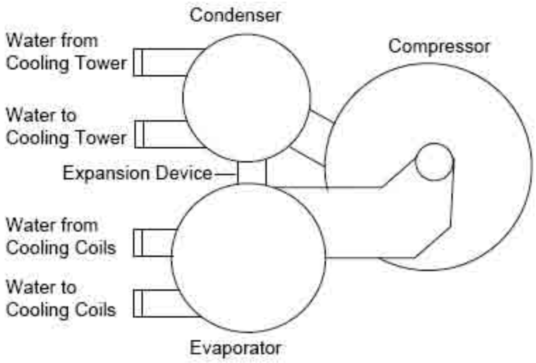


Figure 7. Chiller

Water enters the evaporator and the condenser through external piping. Tubing inside the piping is surrounded by a chiller medium, which is a compressible gas such as freon. As the water circulates within the tubing, heat is transferred between the water and the chiller medium. The chiller medium is subjected to two stages of pressurization. First, the medium is fed into the condenser at high pressure by the compressor. When the medium is compressed, its temperature increases. The chiller medium then leaves the condenser through an expansion device that suddenly lowers the medium's pressure before it enters the evaporator. When the medium is thus expanded, its temperature decreases. The change in pressurization between these two stages is the key to the cooling provided by the chiller.

Heat is removed from the building air as the air passes over coils in the air ducts through which chilled water is flowing. This water flows into the evaporator where the heat is transferred to the chiller medium. The chiller medium is pressurized in the compressor, then transfers the resultant heat energy, which is a combination of the building heat picked up in the evaporator and the effects of compression, into the water in the condenser circuit. The condenser water is pumped into a cooling tower where the heat delivered from the compressor is dissipated into the outside air. In effect, the evaporator acts as a device to absorb heat from the building air while the condenser acts as a device to remove that heat from the building once it is picked up.

COOLING TOWERS

The job of the cooling tower is to radiate the heat of the building. Located on the outside of a building, the tower removes heat from the condenser water as the condenser water removes heat from the chiller (See Figure 8).

Water in a cooling tower is cooled by evaporation. Every pound of water that a cooling tower evaporates removes 1,000 BTU from the system. This lowers the temperature of 1,000 pounds of water by 1 degree Fahrenheit.

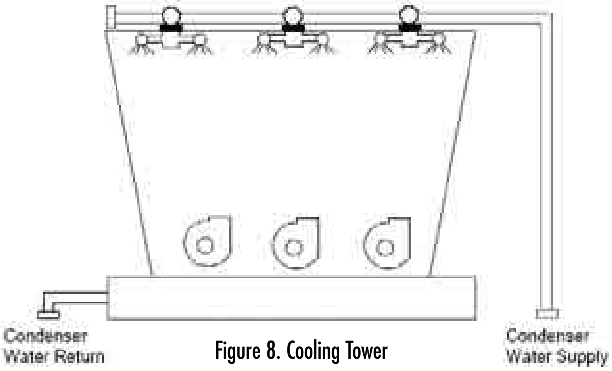


Figure 8. Cooling Tower

The condenser water is released from the top of the tower in a fine spray. The finer the spray, the more surface area is available for evaporation. As the cooling tower fans blow air through the spray, the air carries away some of the heated water vapor, further aiding the evaporation process. Water in the tower cools by about 10 degrees Fahrenheit and is circulated back to the chiller to be heated again by the condenser. The efficiency of evaporation in a cooling tower at any given time is determined by a combination of outside air temperature and humidity. A special type of scale, called wet-bulb temperature, was created for controlling cooling towers. Wet-bulb temperature is determined by a thermometer enclosed in a water-soaked wick. A tower removes heat better on a cool, dry day than on a hot, humid day. This reading is therefore used to control most cooling towers.

DEHUMIDIFYING

Warm air contains more moisture than cool air. The more moisture in the air, the more slowly perspiration evaporates. Since perspiration evaporation is an important mechanism for cooling the human body, high humidity increases discomfort during warm weather. Good HVAC systems not only cool the building, but also remove excess moisture.

Condensation dehumidification is the process most often used in HVAC systems to remove excess moisture from the air. When warm, moist air passes over a cooling coil, its temperature can fall to a point where the air can no longer hold all the moisture it contains. The moisture then condenses on the coil as droplets which may be drained away. Typically, this task is accomplished by the coils using chilled water to cool the building and condensation is simply drained off of these coils as it builds.

PUMPS AND FANS

In order for air and water to be used to control the temperature of a building, there must be a way to move them around in the building. Pumps and fans are similar kinetic devices and both use the same principles to move water and air.

CENTRIFUGAL PUMPS

A centrifugal pump consists of a rotating impeller inside of a specially shaped shell. As the impeller rotates, liquid is taken in at the axis of the impeller and forced out along vanes to its tips. The liquid moves faster at the tips of the impeller than at the axis. The fluid is then gathered in a specially shaped diffusing section called a volute, where it is discharged at high pressure.

PUMPING SYSTEMS

Pumping systems are designed to increase both the flow and pressure of a liquid. In tall buildings, the pressure at which water leaves pumps is critical. Think of a water pipe in a building as a standing column of water. In order to move the water from the bottom up, the water at the bottom has to be pushed up with enough force to overcome the weight of the water above and the friction of the piping system that the water is flowing in. This force is referred to as the total dynamic head of the system.

All of the water systems in a building must be designed to overcome the dynamic head of the system and provide the proper flow and pressure at the water's destination. The water systems in a building include condenser water pumps, chilled water pumps, HVAC hot water pumps, and domestic water pumps.

Municipal water systems are often designed as low-pressure systems. Lower pressure in the system means that there is less stress on pipes and fittings, leading to longer life and lower maintenance costs. Unfortunately, this means that most buildings get water at too low of a pressure.

If a municipal water system only delivers enough pressure to overcome the dynamic head of a two-story building, any building over that height needs booster pumps to increase the pressure after it enters the building. Booster pumps are also required for domestic and HVAC hot water systems. Nearly all buildings have their boilers located in the basement. After the water is heated in the boiler, pumps must be used to give the heated water sufficient pressure to go where needed in the building.

CENTRIFUGAL FANS

Traditional, three-bladed, "propeller-style" fans are not very common. They are often noisy and inefficient. Centrifugal fans are classified according to blade arrangement such as radial, airfoil, and forward curved. Widely used in larger HVAC systems, especially in industry, centrifugal fans move considerable volumes of air over a wide range of pressures.

Centrifugals have a rotating cylinder (impeller) mounted inside a scroll-type housing which somewhat resembles a snail's shell. These fans have scoop-like blades that collect air and throw it against the inside of the housing to create the desired air stream for efficient cooling.

FAN SYSTEM DESIGN

Fans are located in systems according to their intended functions. Supply fans, for example, bring in air and must be placed so that air flows through them into the air ducts. Exhaust fans belong at the other end of the air stream. Fans that supply several spaces at once are centrally located. Otherwise, flow rates to different spaces vary and the fan operates inefficiently, wasting energy.

In designing systems, engineers must take into account the temperature of the air that the fan moves. Cool air is denser than hot air. This affects fan performance and efficiency.

The way that air flows toward a fan is an important factor in determining its efficiency. If the entire air stream moves at uniform speed, for example, all portions of the fan do equal work and efficiency is maximized. If air speed is uneven, the work is unequally distributed, causing a lower operating efficiency. This problem is often solved by placing a length of straight duct at the fan intake. The duct smooths the airflow before the air enters the fan. Proper design of duct work is an art in itself. If this is not done right, the system will have very poor efficiency and could also have significant audible noise problems.

Air-conditioning fans are usually arranged in long, rectangular ducts. Made from galvanized steel, the ducts may be attached to the ceilings, walls, or floors of the conditioned space. Ducts often contain metal vanes that direct the airflow to increase system efficiency. Room air inlets and outlets are customarily rectangular in shape and fitted with a metal grill, which often has dampers that open and close to control flow.

ADJUSTABLE FREQUENCY DRIVES

An adjustable frequency drive is an electronic device that changes the speed of a motor's rotation by changing the frequency of the power being fed to the motor. The relationship between a motor's speed and the frequency of the power fed to the motor is linear. For instance, a motor that is designed to turn at 1,800 revolutions per minute (RPM) when connected to a standard 60 Hz power supply, will turn at 900 RPM when connected to an adjustable frequency drive supplying 30 Hz of power.

USE IN HVAC SYSTEMS

Pump and fan systems are generally designed to use a full-speed, non-reversing motor to drive a mechanical air or water mover. The output of these systems is controlled by mechanically constricting the flow with throttling valves or damping vanes.

Although constricting water or airflow reduces the load on the motor and therefore the power required to run the motor, flow constriction is not very efficient. Running a system this way is like driving a car with the accelerator pressed to the floor while controlling speed with the brake. An adjustable frequency drive, on the other hand, allows precise control of motor output. In the case of centrifugal fans and pumps, there is a significant reduction in the power required to handle the load. This power reduction is due to the fact that most pumps and all fans are variable torque loads.

VARIABLE TORQUE LOADS

In a variable torque load, the torque required to drive the load changes according to the speed. As the speed of a load is reduced, the torque required to drive it is decreased as a square of the speed. For example, at 50 percent speed, only 25 percent of the torque required at full speed is needed to turn the load, as shown in Figure 9.

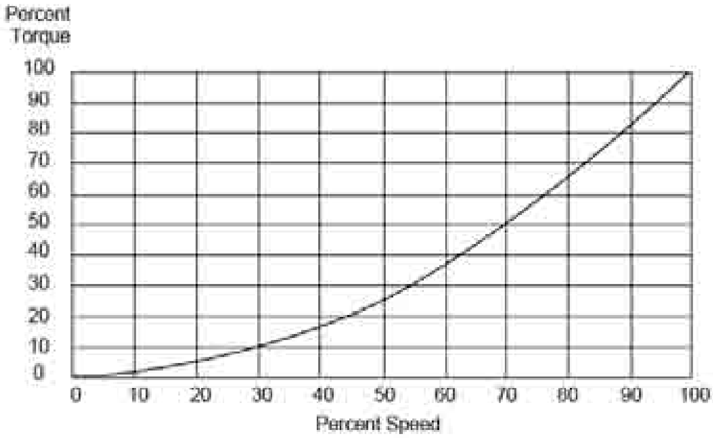


Figure 9. Variable Torque Loads

Fans and pumps are designed to make air or water flow. As the rate of flow increases, the air or water has a greater change in speed put into it by the fan or pump, increasing its inertia. In addition to the inertia change, increased flow means increased friction from the pipes or ducts. An increase in friction requires more force (or torque) to make the air or water flow at that rate.

THE AFFINITY LAWS

The effects that reduced speed has on a variable torque fan or pump are summarized by a set of rules known as the Affinity Laws. The basic interpretation of these laws is quite simple:

1. Flow produced by the device is proportional to the motor speed.
2. Pressure produced by the device is proportional to the motor speed squared.
3. Horsepower required by the device is proportional to the motor speed cubed.

For instance, an adjustable frequency drive running a variable torque load at 50 percent speed needs to deliver only 12.5

percent of the horsepower required to run it at 100 percent speed. The reduction of horsepower means that it costs less to run that motor. When these savings are applied over the yearly hours of operation, significant savings accumulate.

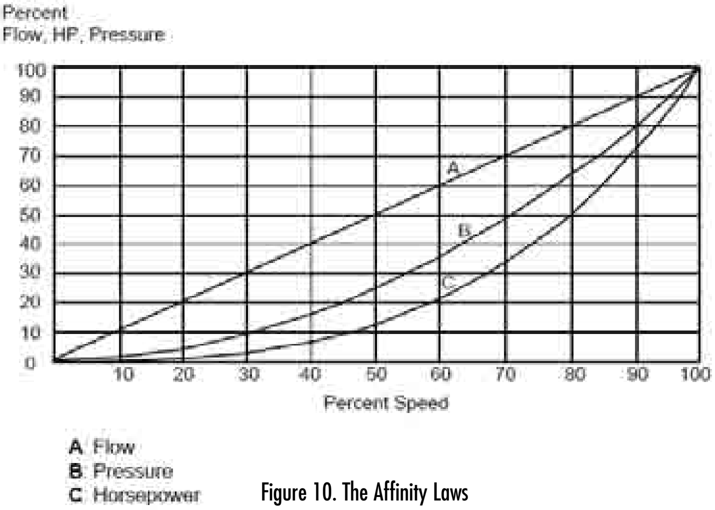


Figure 10. The Affinity Laws

As always, you don't get something for nothing. While the first and third affinity laws allow us to save energy at a reduced speed, the second affinity law shows the effect that this speed reduction has on the pressure that the pump or fan delivers. While this is a significant consideration in most pumping systems, pressure is not as critical in most fan applications. If proper care is taken in engineering the application, adjustable frequency drives can provide significant energy savings for many different installations.

PUMP AND FAN CURVES

As the second affinity law shows, the amount of pressure that a system can deliver is reduced when its speed is reduced. While the affinity law shows a general square relationship, the exact result depends on the specific mechanical design of the fan or pumps system in question.

All fan and pump manufacturers publish performance curves for their products. These curves show what pressures a system produces at reduced speeds. Whenever reduced speed operation is considered, these curves need to be examined in order to determine the speeds at which the fan or pump can run and still make air or water flow.

Consider a pump that produces 140 pounds per square inch (PSI) of pressure when run at full speed. The system that the pump is connected to has a static system pressure of 100 PSI. When variable speed operation is considered for that pump, the pump needs to rotate at a speed that yields at least 100 PSI of pressure or the water will not move. The pump won't even generate enough pressure to overcome the weight of the water above it. In order to determine this minimum speed, the pump curve must be redrawn for variable speed operation using the affinity laws. Reading standard pump or fan curves is fairly straightforward. All of the curves consist of a simple graph with flow rates along the horizontal axis and pressures along the vertical axis. Manufacturers may also add additional scales and curves to the graph to show how efficient the pump is at certain points along the curve and how much brake horsepower is required to drive the pump at those points. More complex publications show curves for multiple impeller or blower sizes on the same graph.

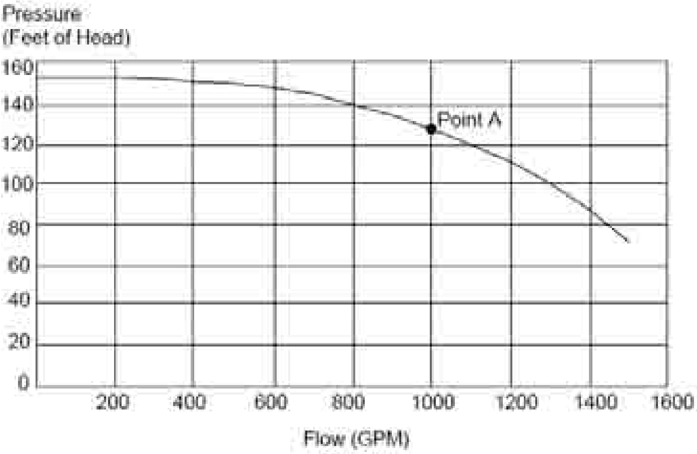


Figure 11. Typical Pump Curve

When a pump or fan is connected to a system, the static and dynamic pressures of that system dictate a natural operating point for that pump or fan. For example, on the pump curve shown in Figure 11, if the system pressures add to 130 PSI, the natural operating point of the system is Point A, at 1,000 gallons per minute (GPM) and 130 PSI. If a system operator wants to generate less than the 1,000 GPM of the natural operating point, a throttling valve is commonly used. As the valve is closed, the operating point moves along the pump curve to the left, increasing pressure as the flow is reduced. As the valve is opened up again, the operating point moves back along the pump curve to the right.

ADJUSTABLE SPEED DRIVES AND PUMP/FAN CURVES

In order to understand the effect that an adjustable frequency drive has on these curves, we need to apply the affinity laws. The curves provided by manufacturers are always based on the operation of the pump or fan at full RPM. Using the first and second affinity laws, a new set of curves can be generated for lower RPMs by simply replotting each point on the curve using the following formulas:

$$\text{New Flow Coordinate} = \text{Original Flow Coordinate} \times \left(\frac{\text{New RPM}}{\text{Original RPM}}\right)$$

$$\text{New Pressure Coordinate} = \text{Original Pressure Coordinate} \times \left(\frac{\text{New RPM}}{\text{Original RPM}}\right)^2$$

Figure 12 shows a typical 60 Hz pump curve with new curves plotted for 50 Hz, 40 Hz, and 30 Hz operation as well.

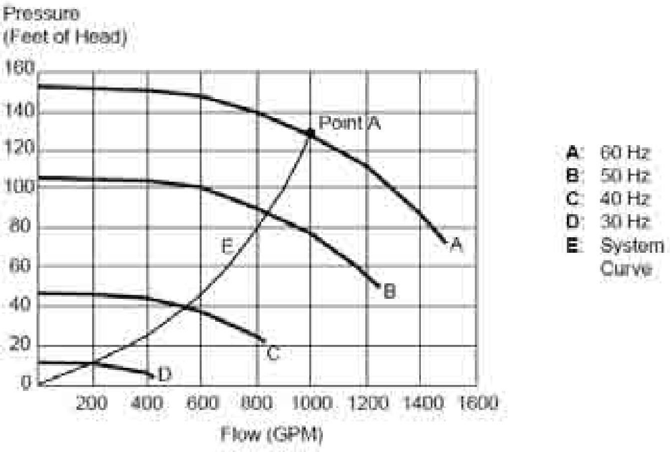


Figure 12. Typical Pump Curve

The same set of formulas allows you to calculate the new position of the operating point for each curve. The curve made up of these operating points is called a system curve. The adjustable frequency drive is only able to reach the pressures and flows that lie along this system curve. Although it is possible to use an adjustable frequency drive and throttling valve in combination to reach any point between the system curve and the original pump curve, such an application is rarely used.

CALCULATING ENERGY SAVINGS

While the theoretical models presented above are quite accurate, when calculating actual energy savings, it is best to take real world efficiencies into account. There are several computer programs available from drive manufacturers that provide more "real world" models of the potential energy savings that adjustable frequency drives yield. Square D has produced software that is based on the "real-world" performance models generated by the Electrical Power Research Institute (EPRI).

VAV FAN SYSTEMS

Variable air volume fan systems have become quite typical in HVAC systems over the past 10 years. A VAV system is designed to maintain a constant static pressure in the air ducts, regardless of the changing demands of the building. Supply and return air fans are connected to the duct work and cycled on and off according to the operating hours of the building. During operation, static pressure sensors in the ducts transmit a signal back to the fans. Inlet vanes or outlet dampers (basically giant louvers) open or close in order to provide the airflow that maintains the desired pressure in the duct. Adjustable frequency drives can replace these vanes, reacting to the same static pressure and control signals being used now. The drive provides the same amount of airflow into the ducts while consuming substantially less energy. The data shown in Figure 13 indicates the difference that an adjustable frequency drive can make in power consumption.

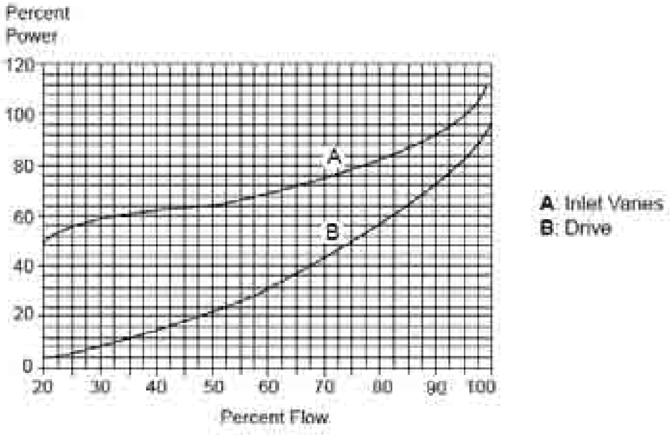


Figure 13. Fan Performance

Based on input of the fan horsepower, motor efficiency, vane type, utility rate, and usage profile, software can calculate the potential annual savings available to the customer. The simple payback period can then be calculated from this data. It is important to note that the estimated savings in these calculations are based on a comparison of vane and damper systems versus adjustable frequency drive systems in new installations. In retrofit applications, the difference between inlet guide vanes and outlet dampers is critical. In the case of outlet dampers, these savings are only valid if the existing dampers are physically removed from the system. If the dampers are left in place, but locked fully open, they will still interfere with airflow and impede system efficiency, resulting in a slight reduction of energy savings. Inlet vanes, on the other hand, should always be left in place. An inlet vane controls airflow by directing the air into the fan. If these vanes are removed, the fan's operating characteristics will be significantly altered. Instead of removing the inlet vanes, they should instead be adjusted to find their optimum operating point and locked in place there.

THROTTLE VALVE CONTROLLED PUMPING SYSTEMS

In some pumping systems, the output of a pump is more than the system requires. This can be the result of either an original over design, or seasonal and daily demand variations. In both of these cases, some sort of throttling valve is used to constrict the output of the pump.

Replacing this valve with an adjustable frequency drive allows for low-speed operation and produces the resultant energy savings.

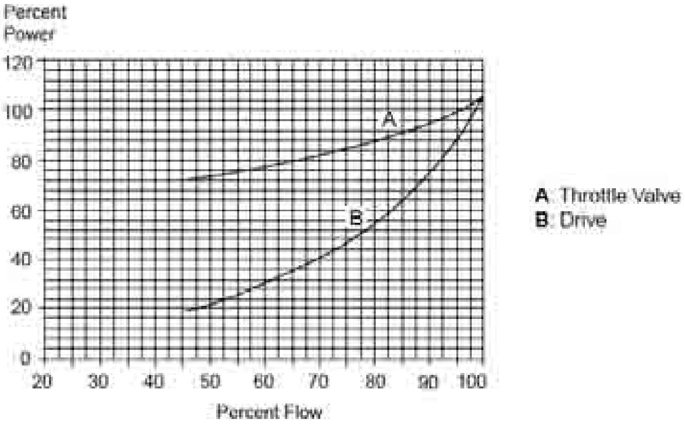


Figure 14. Pump Performance

Based on the input of the pump horsepower, motor efficiency, utility rate, and usage profile, software can calculate the potential annual savings available to the customer. Special care should be taken with discharge pressure when using these pumping systems. As mentioned earlier, there is a reduction in the amount of pressure that can be generated at reduced speeds. This means that in systems with a significant static head on the discharge of the pump, it may not be possible to reduce the speed significantly. On any pumping system, there is a minimum speed at which the pump cannot generate enough pressure to operate in the system. An analysis of the pumping system, including the original pump and system curves, should be made in any pumping application. In all cases, an engineer experienced in adjustable frequency drives should be consulted to determine the feasibility of applying the drives to that particular pumping system.

OTHER APPLICATIONS

In addition to the basic systems discussed above, there are several other typical building systems that are good candidates for adjustable frequency drive applications. All of the systems below are proven applications where energy can be saved using adjustable frequency drives. The savings in these cases can be calculated based on the affinity laws with real world efficiencies factored in.

BANKED FANS

Sometimes buildings are designed with air moving systems that use banks of fans feeding into the same output. As demand changes, the amount of fans on line is changed to adjust the output. Simpler systems also exist where the full output of one fan is all that is ever needed. The fans in these applications are alternated to maximize motor life.

An adjustable frequency drive is an ideal device for this application. Where two fans are available and only one at a time is being used, a drive can be applied to run both at 50 percent speed. This produces the same amount of output while consuming about 14 percent of the power. Keep in mind that the 50 percent operating point is really a theoretical approximation. The exact operating point for this type of application depends on the fan curves and the system using them.

BANKED COOLING TOWER FANS

Cooling towers typically use banks of fans, each feeding cooling cells. In the cells, the fan moves outside air through a spray of water, allowing heat to dissipate from the water. As demand changes and more heat needs to be removed from the water, the amount of cells on line is changed to adjust the output. If an adjustable frequency drive is applied to this system, more cells could be used at one time, while reducing the airflow into them. As in the previous example, the reduced motor speed requires less power to run. In addition to the energy savings from the reduced motor speed, the tower becomes more efficient from the increased surface area being used by the additional cells on-line. This results in even greater overall savings for the building.

PARKING GARAGE EXHAUST FANS

All parking garages are required to run fans during operating hours to remove the auto exhaust fumes. These systems are typically run at full speed at all times. Because traffic in a parking garage varies over the course of a day, there are significant time periods when the garage does not need the same amount of ventilation as during peak traffic periods. The real function of the garage ventilation system is to remove carbon monoxide from the air. A gas-sensing system can be installed to monitor carbon monoxide levels in the garage. This information can in turn be used to adjust fan speed with a control system to keep carbon monoxide levels at a minimum. The system allows for operation at lower speeds and saves energy for the user.

BANKED PUMPS

The banked pumps application is exactly analogous to the banked fans described above. Systems are designed with banks of pumps feeding a common discharge header. Typically, the output of one pump is sufficient for the system and the pumps in these applications are alternated to maximize motor life. An adjustable frequency drive can be applied to run both pumps at 50 percent speed, producing the same amount of output while consuming about 14 percent of the power. As with all pumping systems, pressure becomes a critical part of the application. Banked pumps are not feasible for systems with significant head pressures, but work well with low-pressure systems or systems with pumps able to deliver much greater pressures than the system requires.

VARIABLE SPEED DRIVES

A WAY TO LOWER LIFE CYCLE COSTS

Courtesy: Hydraulic Institute, Europump, and the U.S. Department of Energy's
(DOE) Industrial Technologies Program

INTRODUCTION

Pumping systems account for nearly 20% of the world's energy used by electric motors and 25% to 50% of the total electrical energy usage in certain industrial facilities. Significant opportunities exist to reduce pumping system energy consumption through smart design, retrofitting, and operating practices. In particular, the many pumping applications with variable-duty requirements offer great potential for savings. The savings often go well beyond energy, and may include improved performance, improved reliability, and reduced life cycle costs.

Most existing systems requiring flow control make use of bypass lines, throttling valves, or pump speed adjustments. The most efficient of these is pump speed control. When a pump's speed is reduced, less energy is imparted to the fluid and less energy needs to be throttled or bypassed. Speed can be controlled in a number of ways, with the most popular type of variable speed drive (VSD) being the variable frequency drive (VFD).

Pump speed adjustment is not appropriate for all pumping systems, however. This overview provides highlights from Variable Speed Pumping – A Guide To Successful Applications, which has been developed by Europump and the Hydraulic Institute as a primer and tool to assist plant owners and designers as well as pump, motor, and drive manufacturers and distributors. When the requirements of a pump and system are understood, the user can consult this guide to help determine whether variable speed pumping is the correct choice. The guide is applicable for both new and retrofit installations and contains flowcharts to assist in the selection process.

PUMPING SYSTEMS

A proper discussion of pumping considers not just the pump, but the entire pumping "system" and how the system components interact. The recommended systems approach to evaluation and analysis includes both the supply and demand sides of the system.

PUMPING SYSTEM HYDRAULIC CHARACTERISTICS

In a pumping system, the objective, in most cases, is either to transfer a liquid from a source to a required destination, e.g., filling a high-level reservoir, or to circulate liquid around a system, e.g., as a means of heat transfer. Pressure is needed to make the liquid flow at the required rate and this must overcome losses in the system. Losses are of two types: static and friction head. Static head, in its most simple form, is the difference in height of the supply and destination of the liquid being moved, or the pressure in a vessel into which the pump is discharging, if it is independent of flow rate. Friction head (sometimes called dynamic head loss), is the friction loss on the liquid being moved, in pipes, valves, and other equipment in the system. This loss is proportional to the square of the flow rate. A closed-loop circulating system, without a surface open to atmospheric pressure, would exhibit only friction losses.

VARIABLE SPEED PUMPING – A GUIDE TO SUCCESSFUL APPLICATIONS

Most systems have a combination of static and friction head. The ratio of static to friction head over the operating range influences the benefits achievable from VSDs. Static head is a characteristic of the specific installation. Reducing this head whenever possible generally reduces both the cost of the installation and the cost of pumping the liquid. Friction head losses must be minimized to reduce pumping cost, but after eliminating unnecessary pipe fittings and length, further reduction in friction head will require larger diameter pipes, which adds to installation cost.

PUMP TYPES

Proper selection of pumps, motors, and controls to meet the process requirements is essential to ensure that a pumping system operates effectively, reliably, and efficiently. All pumps are divided into the two major categories of positive displacement (PD) and rotodynamic.

PD pumps can be classified into two main groups: rotary and reciprocating. Rotary pumps typically work at pressures up to 25 Bar (360 pounds per square inch [psi]). These pumps transfer liquid from suction to discharge through the action of rotating screws, lobes, gears, rollers, etc., which operate within a rigid casing. Reciprocating pumps typically work at pressures up to 500 Bar. These pumps discharge liquid by changing the internal volume. Reciprocating pumps can generally be classified as having a piston, plunger, or diaphragm, displacing a discrete volume of liquid between an inlet valve and a discharge valve. The rotary motion of the driver, such as an electric motor, is converted to the reciprocating motion by a crankshaft, camshaft, or swash-plate.

The performance of a pump can be expressed graphically as head against flow rate. The rotodynamic pump has a curve where the head falls gradually with increasing flow. However, for a PD pump, the flow is almost constant whatever the head. It is customary to draw the curve for PD pumps with the axes reversed, but for comparison, a common presentation is used here for the two pump types.

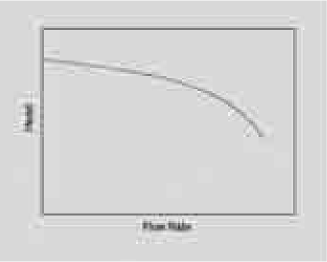


Figure ES-1. Performance curve for a rotodynamic pump

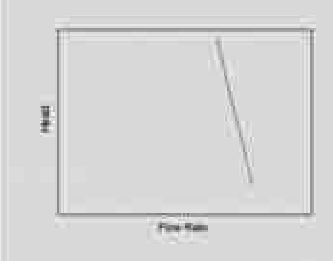


Figure ES-2. Performance curve for a positive displacement pump

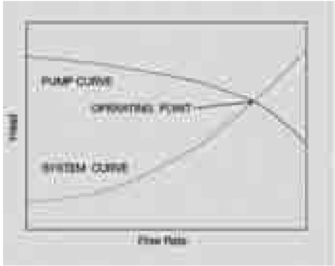


Figure ES-3. System curve and a performance curve for a rotodynamic pump

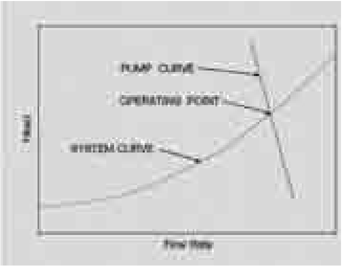


Figure ES-4. System curve and a performance curve for a positive displacement pump

INTERACTION OF PUMPS AND SYSTEMS

When a pump is installed in a system, the effect can be illustrated graphically by superimposing pump and system curves. The operating point will always be where the two curves intersect.

For a PD pump, if the system resistance increases, i.e., the system curve is moved upwards, the pump will increase its discharge pressure and maintain a fairly constant flow rate, dependent on viscosity and pump type. Unsafe pressure levels can occur without relief valves. For a rotodynamic pump, an increasing system resistance will reduce the flow, eventually to zero, but the maximum head is limited.

Even so, this condition is only acceptable for a short period without causing problems. Adding comfort margins to the calculated system curve to ensure that a sufficiently large pump is selected will generally result in installing an oversized pump. The pump will operate at an excessive flow rate or will need to be throttled, leading to increased energy use and reduced pump life. Many pumping systems require a variation of flow or pressure. Either the system curve or the pump curve must be changed to get a different operating point. Where a single pump has been installed for a range of duties, it will have been sized to meet the greatest output demand. It will therefore usually be oversized, and will be operating inefficiently for other duties. Consequently, there is an opportunity to achieve an energy cost savings by using control methods, such as variable speed, which reduce the power to drive the pump during the periods of reduced demand.

EFFECTS OF SPEED VARIATION ON ROTODYNAMIC PUMPS

A rotodynamic pump is a dynamic device with the head generated by a rotating impeller. Thus, there is a relationship between impeller peripheral velocity and generated head. Peripheral velocity is directly related to shaft rotational speed, for a fixed impeller diameter. Varying the rotational speed therefore has a direct effect on the pump's performance. The equations relating rotodynamic pump performance parameters of flow to speed, and head and power absorbed to speed, are known as the Affinity Laws.

Changing pump impeller diameter also effectively changes the duty point in a given system, and at low cost, but this can be used only for permanent adjustment to the pump curve and is not discussed further as a control method. For systems where friction loss predominates, reducing pump speed moves the intersection point on the system curve along a line of constant efficiency (see Figure ES-5). The operating point of the pump, relative to its best efficiency point, remains constant and the pump continues to operate in its ideal region. The Affinity Laws are obeyed, which means that there is a substantial reduction in power absorbed accompanying the reduction in flow and head, making variable speed the ideal control method.

However, in systems with high static head, the system curve does not start from the origin but at some non-zero value on the y-axis corresponding to the static head. Hence, the system curve does not follow the curves of constant efficiency. Instead, it intersects them (see Figure ES-6). The reduction in flow is no longer proportional to speed; a small turn down in speed greatly reduces flow rate and pump efficiency. A common mistake is to also use the Affinity Laws to calculate energy savings in systems with static head. Although this may be done as an approximation, it can also lead to major errors.

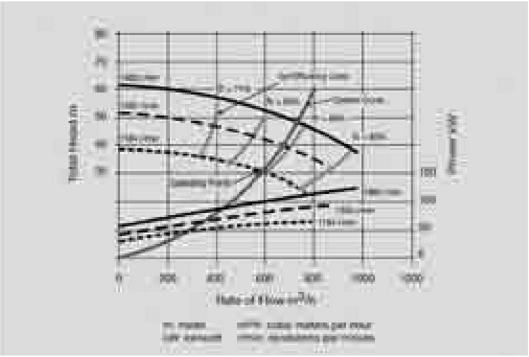


Figure ES-5. Example of the effect of pump speed change in a system with only friction loss

It is relevant to note that flow control by speed regulation is always more efficient than by a control valve. In addition to energy savings, there could be other benefits to lower speed. The hydraulic forces on the impeller, created by the pressure profile inside the pump casing, reduce approximately with the square of speed. These forces are carried by the pump bearings, and so reducing speed increases bearing life. It can be shown that for a rotodynamic pump, bearing life is proportional to the seventh power of speed. In addition, vibration and noise are reduced and seal life is increased, provided that the duty point remains within the allowable operating range.

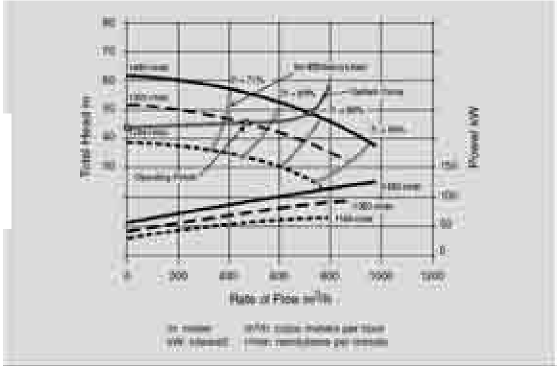


Figure ES-6. Example of the effect of pump speed change in a system with high static head

EFFECT OF SPEED ON PUMP SUCTION PERFORMANCE

Liquid entering the impeller eye turns and is split into separate streams by the leading edges of the impeller vanes, an action that locally drops the pressure below that in the inlet pipe to the pump. If the incoming liquid is at a pressure with insufficient margin above the vapor pressure, then vapor cavities, or bubbles, appear along the impeller vanes just behind the inlet edges. These collapse further along the impeller vane where the pressure has increased. This phenomenon is known as cavitation, and has undesirable effects on pump life. Increasing pump speed will negatively affect pump suction performance and should be thoroughly investigated. Conversely, reducing speed will have a positive effect.

EFFECTS OF SPEED VARIATION ON POSITIVE DISPLACEMENT PUMPS

To control flow in a PD pump, the speed needs to be changed or some of the flow has to be diverted. Throttling is not effective and is potentially dangerous. For many applications, some small flow rate changes need to be made while holding the pressure constant, and this is best achieved with a pressure-regulating valve. Such a valve will spill a small amount of liquid back to the source to maintain a constant system pressure. This will accommodate small amounts of wear in any restricting device; however, the use of such a valve to spill large volumes of liquid will be very inefficient, with the loss of energy manifesting as heat and noise.

A VSD is the preferred option for an application where the flow needs to vary on a regular basis. This is the most efficient method of flow control and it does not waste any of the shaft input energy.

For a PD pump, the flow is proportional to speed, but the pressure can be independent of speed. Consequently, power and energy savings do not fall so quickly when speed is reduced. Sometimes it is necessary to operate PD pumps over a wider speed range than rotodynamic pumps, typically up to 10:1. This large speed range and the characteristics of PD pumps have implications for both the pump and the drive train, including:

- Lower or higher operating speeds may require special consideration with respect to the method or type of lubrication and/or cooling.
- The motor may not be adequately cooled at the lowest speed. A separately driven fan may need to be considered.
- The flow rate may be so low that the valve opening is too small to be sustainable under the different forces, and the valve could flutter.
- The energy from the drive-train inertia becomes too small to smooth the torque ripple and the motor starts to hunt. Two possible solutions are a motor running at a higher speed with a bigger drive-train reduction ratio, or a compensating flywheel.
- At the system design stage, the constant torque characteristic and possible low-speed torque effects must be considered, because they impose demands on electronic VSDs.
- When liquids containing solids with a high settling rate are pumped, excessive solids accumulation can occur in the pump, causing wear. It is paramount, when reducing speed with such liquids, that the velocity be maintained high enough in the pump and in the pumping system to avoid settling out of the solids.
- A change in liquid temperature and viscosity could lead to cavitation.

MOTORS

There are many types of pump prime movers available (such as diesel engines and steam turbines) but the majority of pumps are driven by an electric motor. Although this guide is principally about pumps and VSDs, it is important to appreciate that, on a typical industrial site, motor-driven equipment accounts for approximately two-thirds of electricity consumption. Improvements in motor efficiency, by using high-efficiency motors, can offer major energy savings and short payback. Many of the principles outlined in the guide apply to all motors on a site, not just those used as pump prime movers.

VARIABLE SPEED DRIVES

There are several types of VSDs, as shown in Figure ES-7. In applications that require flow or pressure control, particularly in systems with high friction loss, the most energy-efficient option for control is an electronic VSD, commonly referred to as a variable frequency drive (VFD). The most common form of VFD is the voltage- source, pulse-width modulated (PWM) frequency converter (often incorrectly referred to as an inverter). In its simplest form, the converter develops a voltage directly proportional to the frequency, which produces a constant magnetic flux in the motor. This electronic control can match the motor speed to the load requirement.

This eliminates a number of costly and energy inefficient ancillaries, such as throttle valves or bypass systems.

SELECTION PROCESS – NEW SYSTEMS

It is essential to commence the sizing exercise with the hydraulic system, and to work systematically to select the pump, motor, and drive. When the pump maximum duty is known, the peak power and speed for the drive will become clear. It is common to oversize system components (pumps, motors, and drives); however, this practice is not recommended because it leads to higher initial equipment costs and higher life cycle costs.

When selecting a rotodynamic pump in combination with a VSD for a system with some static head, a pump should be chosen such that the maximum flow rate is slightly to the right-hand side of the best efficiency point (BEP). The exception is for a constant flow regulated system, in which case the recommendation is to select a pump that operates to the left of BEP at maximum pressure. This approach optimizes pump operating efficiency.

All operating conditions must be considered when designing the system. Some operating profiles may be satisfied best by installing multiple pumps, which could be fixed or variable speed. On/off control can be used to vary flow rate for systems in which an intermittent flow is acceptable. This can be an energy-efficient solution, but these systems often require a liquid storage facility.

SELECTION PROCESS – RETROFITTING TO EXISTING EQUIPMENT

There are approximately 20 times more pumps in service than are supplied new every year. It is therefore apparent that a major opportunity exists for modifying installed systems to make them more energy efficient. Most system designers allow a contingency on the system head required. It is estimated that 75% of pump systems are oversized, many by more than 20%. It follows that retrofitting with VSDs could match pump systems to actual system requirements more accurately and save considerable amounts of energy.

When considering adding a VSD to an existing motor, care should be taken to match the electrical characteristics of the motor and frequency converter; otherwise, the risk of premature failure is introduced into the system. Early frequency converters produced outputs with a very high harmonic content in the waveform, which caused substantial additional heating of motor windings, and therefore motors were derated for inverter use. A modern inverter output causes relatively small levels of harmonic current distortion in the motor windings, and therefore little derating is normally required. High-efficiency motors are less affected by harmonics than standard efficiency types.

BENEFITS OF VSDS

VSDs offer several benefits, some of which are relatively easy to quantify, and others of which are less tangible, but there are some potential drawbacks, which must be avoided.

ENERGY SAVINGS

With rotodynamic pump installations, savings of between 30% and 50% have been achieved in many installations by installing VSDs. Where PD pumps are used, energy consumption tends to be directly proportional to the volume pumped and savings are readily quantified.

IMPROVED PROCESS CONTROL

By matching pump output flow or pressure directly to the process requirements, small variations can be corrected more rapidly by a VSD than by other control forms, which improves process performance. There is less likelihood of flow or pressure surges when the control device provides rates of change, which are virtually infinitely variable.

IMPROVED SYSTEM RELIABILITY

Any reduction in speed achieved by using a VSD has major benefits in reducing pump wear, particularly in bearings and seals. Furthermore, by using reliability indices, the additional time periods between maintenance or breakdowns can be accurately computed.

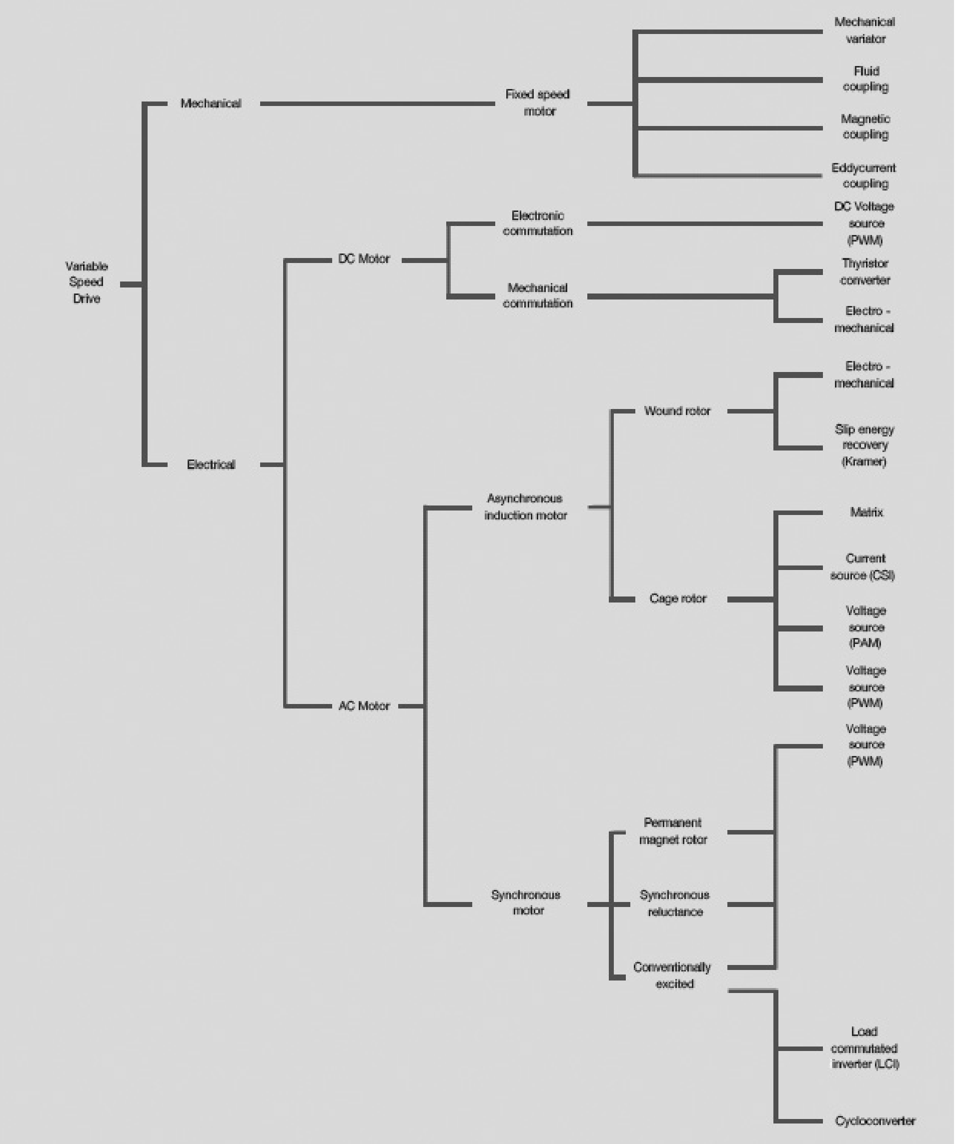


Figure ES-7. Types of Variable Speed Drives

POTENTIAL DRAWBACKS OF VSDS

VSDs also have some potential drawbacks which can be avoided with appropriate design and application.

STRUCTURAL RESONANCE

Resonance conditions can cause excessive vibration levels which, in turn, are potentially harmful to equipment and environment. Pumps, their support structure, and piping are subject to a variety of potential structural vibration problems (resonance conditions). Fixed-speed applications often miss these potential resonance situations because the common excitation harmonics due to running speed, vane passing frequency, plunger frequency, etc., do not coincide with the structural natural frequencies. For VSD applications, the excitation frequencies become variable and the likelihood of encountering a resonance condition within the continuous operating speed range is greatly increased. Pump vibration problems typically occur with bearing housings and the support structure (baseplate for horizontal applications, motor and stool for vertical applications).

Pressure pulsations are the common excitation mechanism. These pressure pulsations may be further amplified by acoustic resonance within the pump or the adjacent piping. There are a number of analyses that can be performed to predict and avoid potential resonance situations, including:

- Simple hydraulic resonance calculations
- Passing frequency analysis
- Structural resonance, for example, utilizing Finite Element Analysis
- Modal testing of the actual machine.

Modal testing can supplement the regular vibration test. Very often, a pump intended for variable speed operation will only be tested at one single speed.

ROTOR DYNAMICS

The risk of the rotating element encountering a lateral critical speed increases with the application of a VSD. Lateral critical speeds occur when running speed excitation coincides with one of the rotor's lateral natural frequencies. The resulting rotor vibration may be acceptable or excessive, depending on the modal damping associated with the corresponding mode. Additionally, drive-induced torque harmonics may cause resonance conditions with torsional rotor dynamic modes. However, such conditions are usually correctible or preventable. Variable speed vertical pumps are more likely than horizontal machines to exhibit operational zones of excessive vibration. This is because such pumps' lower natural frequencies are more likely to coincide with running speed. Small, vertical closecoupled and multistage pumps normally do not present this type of problem.

ADDITIONAL CONSIDERATIONS FOR VFDS

The introduction of VFDs requires additional design and application considerations. VFDs can be fitted to most existing motors in Europe and other areas, which use a 400 Volt (V) network. However, this is generally not the case in the United States, and other areas where network voltages exceed 440 V. Hence, reinforced insulation "inverter duty" motors are often needed. The high rate of switching in the PWM waveform can occasionally lead to problems.

For example:

- The rate of the wavefront rise can cause electromagnetic disturbances, requiring adequate electrical screening (screened output cables). Filters in the inverter output can eliminate this problem.
- Older motor insulation systems may deteriorate more rapidly due to the rapid rate of voltage change. Again, filters will eliminate this problem.
- Long cable runs can cause "transmission line" effects, and cause raised voltages at the motor terminals. Voltages can be induced in the shafts of larger motors, potentially leading to circulating currents which can destroy bearings. The following corrective measures are required:
- Insulated non-drive-end bearings are recommended on all motors over 100 kilowatt (kW) output rating.
- Common mode filters may additionally be required for higher powers and voltages.

The converter will have losses, and ventilation requirements for the electronics can be an important issue. The life expectancy of the converter is generally directly related to the temperature of the internal components, especially capacitors. The converter may require installation in a less onerous environment than the motor control gear it replaces. Specifically:

- Electronics are less able to cope with corrosive and damp locations than conventional starters.
- Operating a VFD in a potentially explosive atmosphere is not usually possible.

ESTIMATING PUMPING ENERGY COSTS

To compare different system and pumping equipment proposals and make an intelligent choice, some basic facts will need to be established.

- Will the process require varying flow rate and, if so, must it be continuously variable or can flow rate be varied in steps?
- Can on-off batch pumping be used?
- What is the peak flow rate and how is the flow rate distributed over time?

The answers to these questions will determine if, and how, to regulate the flow. It will also give some guidance regarding the pumping system design. A helpful way of showing the flow demand is to use a duration diagram. A duration diagram in its simplest form (see Figure ES-8) shows how many hours during a year that a given flow rate is needed – the dashed line. The solid curve in the same diagram is interpreted differently. Each point on the solid curve tells how many hours during a year the flow rate exceeds the value on the y-axis.

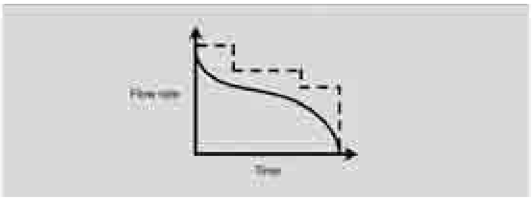


Figure ES-8. Example of a duration diagram

This diagram is instrumental in understanding the pumping needs. The system must be able to deliver the peak flow but, from an economic point of view, it is also important to know at what flow rates the system is going to operate most of the time. To find the total cost of operating the pump, the running cost at each operating condition must be calculated and summated.

CAPITAL COST SAVINGS

When designing and installing a new pumping system, the capital cost of a VSD can often be offset by eliminating control valves, bypass lines, and conventional starters, as explained below.

ELIMINATION OF CONTROL VALVES

Control valves are used to adjust rotodynamic pump output to suit varying system requirements. Usually a constant-speed pump is pumping against a control valve, which is partially closed for most of the time. Even at maximum flow conditions, a control valve is normally designed to be 10% shut, for control purposes. Hence, a considerable frictional resistance is applied. Energy is therefore wasted overcoming the added frictional loss through the valve. Using a VSD to control flow can eliminate the control valve.

ELIMINATION OF BYPASS LINES

All fixed-speed centrifugal pumps have a minimum flow requirement. If the pump is operated at flow rates below the minimum for extended periods, various mechanical problems can occur. If the flow requirements in a system can drop below this minimum flow capacity, it is necessary to install a constant or switched bypass to protect the pump. The use of a VSD greatly reduces the volume to be bypassed.

FINANCIAL JUSTIFICATION

The initial cost of pumping equipment is often a very small part of the total life cycle cost (LCC). An LCC analysis is therefore a very appropriate way to compare different technical alternatives in the design of a pumping system and make a financial justification. The components of an LCC analysis typically include initial costs, installation and commissioning costs, energy costs, operation costs, maintenance and repair costs, downtime costs, environmental costs, and decommissioning and disposal costs (see Figure ES-9). The LCC equation can be stated as:

$$LCC = C_{ic} + C_{in} + C_e + C_o + C_m + C_s + C_{env} + C_d$$

C = cost element
ic = initial cost, purchase price (pump, system, pipes, auxiliaries)
in = installation and commissioning
e = energy costs
o = operating cost (labor cost of normal system supervision)
m = maintenance cost (parts, man-hours)
s = downtime, loss of production
env = environmental costs
d = decommissioning

A very well documented guide, *Pump Life Cycle Costs: LCC Analysis for Pumping Systems*[1], has been published jointly by Hydraulic Institute and Europump. This guide explains how the operating costs of a pumping system are influenced by system design and shows in detail how to use a life cycle cost analysis to make comparative cost assessments. Many case studies have been included in the guide to highlight the value of possible savings in real applications.

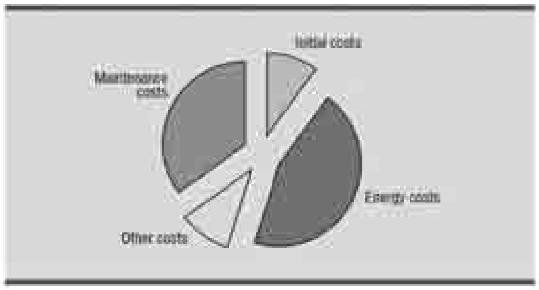


Figure ES-9. Typical LCC components for a medium sized industrial pumping system

EXAMPLE: VARIABLE SPEED DRIVES FITTED ON A PRIMARY FEED PUMP AND PRODUCT TRANSFER PUMP IN A REFINERY

SUMMARY

At a San Francisco refinery, installing a VFD on a product transfer pump saved €/$120,000 (euros/U.S. dollars) per year, and on a primary feed pump, saved €/$220,000. Vibration was reduced and mechanical seal and bearing failures have been eliminated. There was no investment cost to the refinery, but savings were shared with the contractor who provided the capital investment.

OTHER POTENTIAL APPLICATIONS

Suitable applications include any in which the pump is sized for an intermittent maximum flow rate but runs mostly at a reduced (but variable) rate.

INVESTMENT COST

The energy services contractor agreed to install the VFDs and upgrade the equipment at no charge to the refinery, but took a share of the savings. The total investment was €/$1.2 million.

SAVINGS ACHIEVED

Over the course of a year, the VFDs saved €/$340,000 and the total project saved €/$750,000 per year.

PAYBACK PERIOD

Overall payback was about 1.6 years, but this was not applicable to the refinery, which gained immediately with its share of the savings.

INSTALLATION AND OPERATION DETAILS

Conversion of the refinery's vacuum gas oil plant to a Diesel Hydro Treater (DHT) left the pumps grossly oversized. Several were often operating at 40% of best efficiency point, causing low hydraulic efficiency, excessive vibration, and seal or bearing failure about once a year.

The full range of upgrades consisted of:

- Installing VFDs on the 1,650-kW (2,250-horsepower [hp]) primary feed pump and on the 500-kW (700-hp) product transfer pump
- Replacing the internal elements on the 1,650-kW (2,250-hp) secondary feed pump and on a 400-hp Power Recover Turbine (PRT)
- Changing operating procedures for the main 3,700-kW (5,000-hp) and 3,000-kW (4,000-hp) back-up pumps.

Installing the VFDs on the primary feed pump and product transfer pump saved energy by reducing losses through flow control valves. The energy saved from using VFDs was 500,000 kWh per month. Resizing the PRT and secondary feed pump, along with a more energy-efficient operating procedure for the back-up pumps, saved another 500,000 kWh per month. Cost savings shared by the refinery and contractor were €/$340,000 from the variable speed pumps and €/$750,000 overall. The demand charge previously levied on the DHT process was eliminated. Since the upgrade, there have been no seal or bearing failures and process control has improved. It should be noted that a VFD was not considered appropriate for all the oversized pumps. If the flow rate does not vary, then resizing the pump (e.g., replacing the impeller and diffuser element), reduced impeller diameters, or even a new pump will usually give greater lifetime cost savings and better payback than a VSD.

ELEVATOR DRIVE CONTROL SYSTEMS

by Shigeki Yamakawa and Hiroshi Gokan* Courtesy: Mitsubishi Electric

*Shigeki Yamakawa is with the Inazawa Works and Hiroshi Gokan is with the Design Systems Engineering Center.

Mitsubishi Electric has developed a new elevator-control ASIC that is more highly integrated with better control performance than the company's first elevator control LSIs released in 1995. The company's first car control system employed two microprocessors, one for sequencing and speed control, the other to generate PWM current control signals for the converter and inverter.

All major functional blocks – the elevator current-control processor, PWM generator and the 8-bit speed feedback processor – have been integrated into a monolithic device, reducing the size and complexity of the peripheral circuits. Better arithmetic processing performance provides improved current-control response, implementing short-circuit protection and controlling torque ripple without the voltage feedback circuit previously used for this purpose.

Engineering the device required development of tools for design and verifying system behavior. Development time was reduced by developing hardware and software concurrently.

CONTROL SYSTEM

Fig. 1 shows the control system configuration for a high-speed elevator. Fig. 2 shows the functional blocks of the elevator control ASIC, which we call AML for "associated management logic." Most of the logic functions for controlling the elevator and its traction motor are contained in this single device. The few external components include the car control processor (CCP) and ADCs.

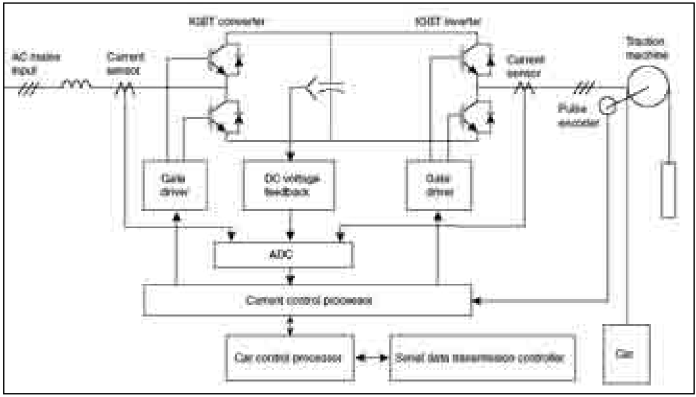


Figure 1. Configuration of high-speed elevator control system

The motor control processor (MCP) is an original RISC processor core developed to generate current-control commands for the inverter and converter. The PWM unit generates pulse-width modulated signals corresponding to the MCP current commands. The encoder counting unit (ECU) tallies pulses from encoders and generates phase data for the MCP and speed and position data for the CCP. The CCP is an external 32-bit processor that performs car equipment sequencing and processes user commands to implement the highest level of elevator control. The CCP exchanges data with the MCP via dual-port memory on the AML chip using bus control logic also contained on the AML chip.

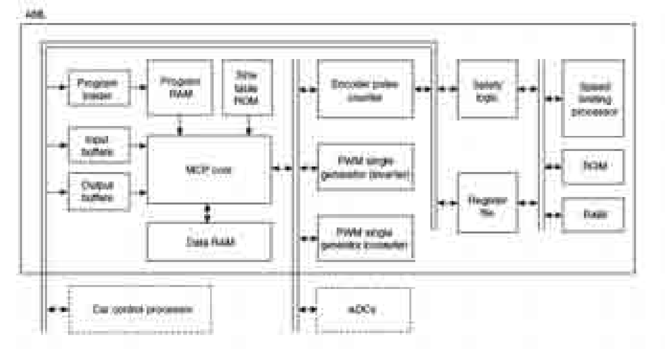


Figure 2. AML chip configuration

MCP CALCULATION PERFORMANCE

The 6µs inverter dead time (Td) in previous systems would result in error in the output-current zero-cross point, requiring addition of a voltage feedback circuit. The faster current calculations of the new MCP permit the current feedback loop to respond more quickly, reducing distortion in the output current waveforms so that motor control is more accurate. Tests on an actual elevator were used to verify that the intended current control response would be fast enough to eliminate these error sources and with them, the need for a voltage feedback circuit. Fig. 3 shows car vibration for various crossover current angular frequencies in a high-speed elevator operating at low speed. The data in Fig. 3a is for a conventional control system with a voltage-feedback circuit to compensate for Td.

The system in Fig. 3d shows comparable performance without a compensation circuit for _c = 5,000 radians/s. This capability was achieved by reducing the time required for the MCP to complete a current calculation cycle to under 50µs.

MCP DATA TRANSFER SYSTEM

On initialization, the CCP reads the MCP control program from external flash memory and loads it into synchronous SRAM located directly on the AML chip. This allows the software to be easily updated to accommodate increases in processor speed and other improvements. The SRAM's fast access allows one instruction to be executed per clock cycle at speeds up to 40MHz. Following initialization in the normal operating mode, the CCP transfers torque command values to the MCP at 5ms intervals. The MCP uses these commands to calculate corresponding converter and inverter current values at 50us intervals.

Independent data registers on both devices allow data transfers despite the different device operating speeds.

MCP CORE CONFIGURATION

An original RISC core was designed to perform current control calculations while permitting integration on the AML chip. We analyzed the motor control software instructions and adopted a 16-bit fixed-length word instruction set with 48 instructions. Fig. 4 shows the core configuration.

Arithmetic, specifically 32-bit addition and 16-bit multiplication, is performed by a 32-bit fixed-point processor. A three-stage load-calculates-store pipeline with parallel execution permits one instruction to be executed per clock cycle. An original assembler was written to support operating software development.

TOP-DOWN DESIGN METHODOLOGY

Fig. 5 shows the flow of the process used to design and verify the AML chip's functionality. We used the best available development tools to design and verify each functional block. Designs for the high-level circuits of the MCP core were entered and their functions simulated using the Zuken-Vps virtual prototyping tool. Design entry for the rest of the circuit blocks was conducted using Verilog's Hardware Description Language (HDL) with functional simulation performed using Verilog-XL from Cadence Design Systems. Logic synthesis was conducted using Design Compiler from Synopsys Inc. Static timing analysis tools supplied by the ASIC vendor were used to reduce the time required for delay simulations. Scan path design automatic test pattern generation was used to support a fully concurrent design process.

AML CHIP DEBUGGING

Fig. 6 shows the debugging process flow. We used a virtual debugging method in which the MCP operation is expressed in C and linked with the Matlab control system analysis tool from The Mathworks, Inc. to analyze the converter and inverter operation. Meanwhile, machine code compiled using the MCP assembler is loaded onto the MCP logic circuits designed on Zuken-Vps and operation is simulated. The register contents of the two simulations are compared with identical register contents taken as acceptance criteria.

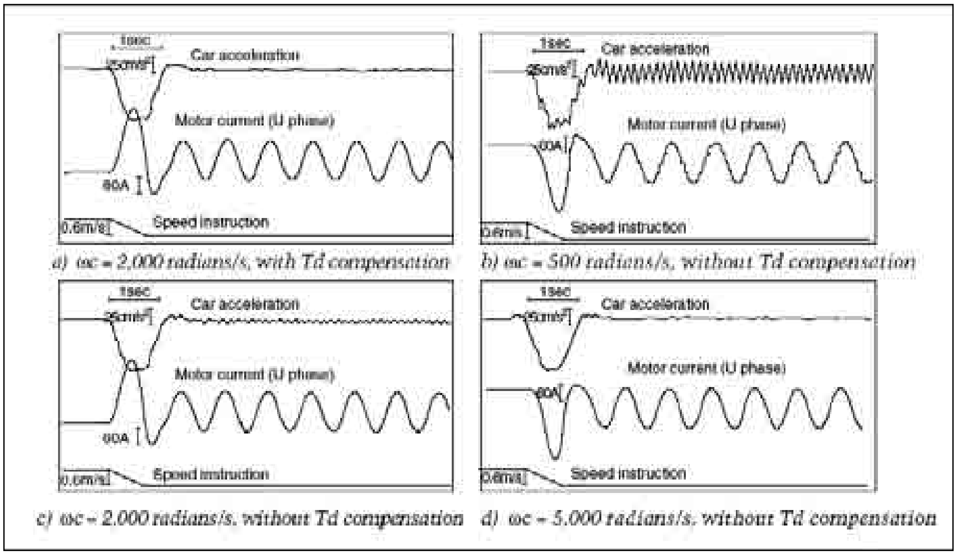
BREADBOARD QUALIFICATION

Prior to fabricating the AML chip, we constructed an equivalent logic prototype controller using six field-programmable gate arrays (FPGAs) and one masked gate array device.

Hardware and software debugging was performed using this controller to operate an actual elevator in a test building.

The AML elevator control ASIC cuts the size and cost of elevator control units.

Development of the 250,000 gate device was completed in ten months, and methods to support larger device scales were established.



a) ωc = 2,000 radians/s, with Td compensation

b) ωc = 500 radians/s, without Td compensation

c) ωc = 2,000 radians/s, without Td compensation

d) ωc = 5,000 radians/s, without Td compensation

Figure 3. Relationship between crossover angular frequency wc and car acceleration for Td=6μs and a balanced load

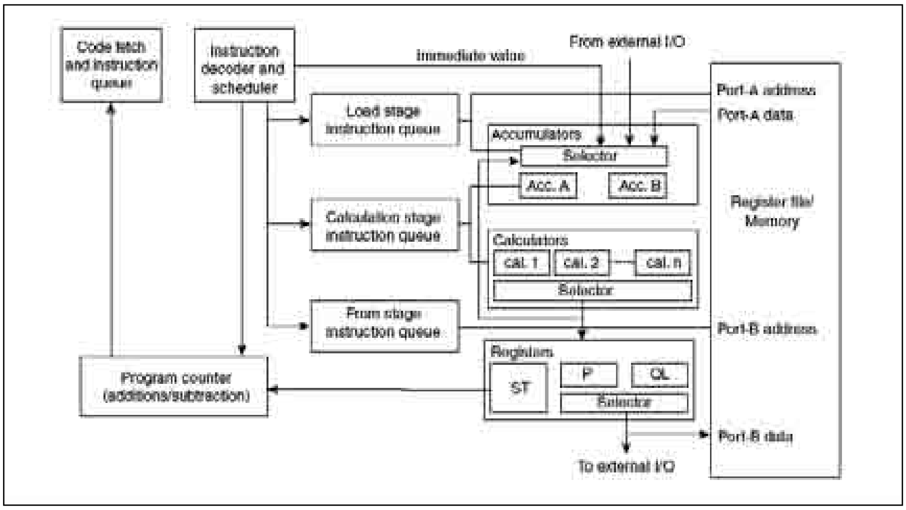


Figure 4. Configuration of MCP core

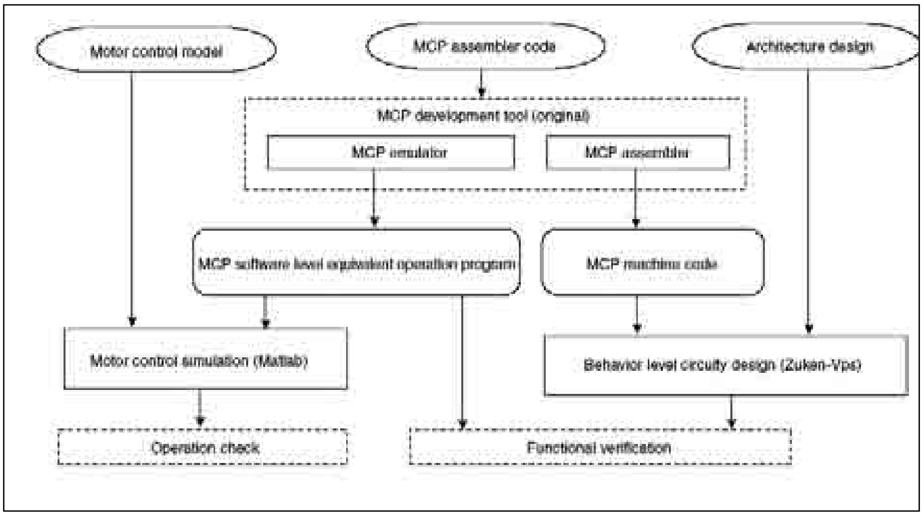

Motor control model
MCP assembler code
Architecture design
MCP development tool (original)
MCP simulator
MCP assembler
MCP software level equivalent operation program
MCP machine code
Motor control simulation (Matlab)
Behavior level circuity design (Zuken-Vps)
Operation check
Functional verification

Figure 5. MCP debugging flow

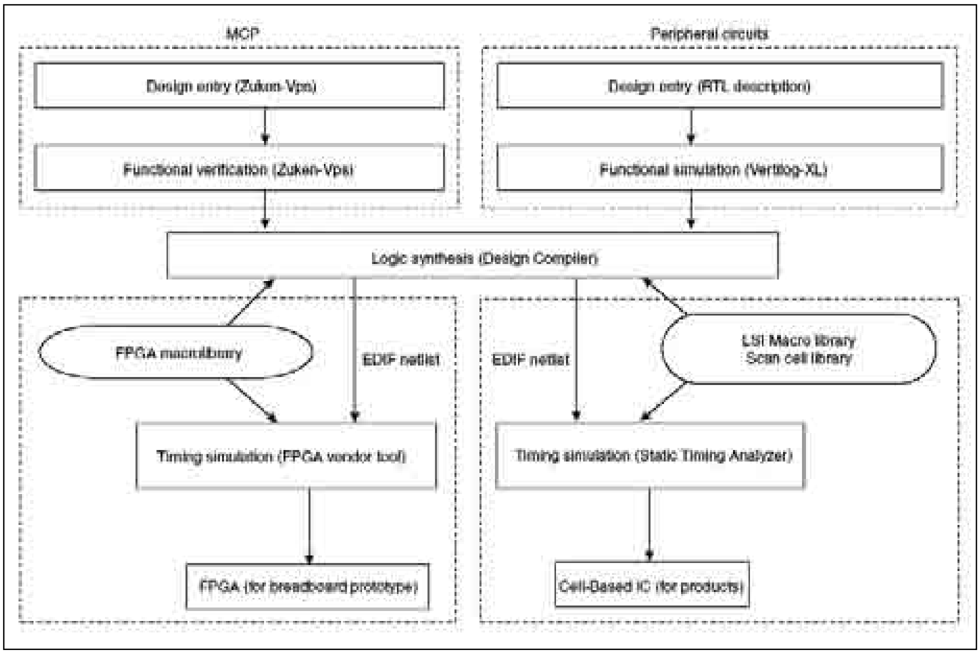

MCP
Peripheral circuits
Design entry (Zuken-Vps)
Design entry (RTL description)
Functional verification (Zuken-Vps)
Functional simulation (Verilog-XL)
Logic synthesis (Design Compiler)
FPGA macrolibrary
EDIF netlist
EDIF netlist
LSI Macro library
Scan cell library
Timing simulation (FPGA vendor tool)
Timing simulation (Static Timing Analyzer)
FPGA (for breadboard prototype)
Cell-Based IC (for products)

Figure 6. AML design flow

APPLICATION OF BRUSHLESS DC DRIVES IN BLOW MOLDING

BY EDWARD C. LEE, POWERTEC INDUSTRIAL CORPORATION

Abstract: Variable speed drives used in Blow Molding have changed little in the last 20 years or more even though substantial technology advances have taken place in other areas of the Blow Molding process. A new variable speed technology has become available in the last 5 years and several blow molding manufacturers and users have taken advantage of this advancement and are using Brushless D.C. drives for the extruder function as well as for rotating molds. This paper addresses the advantages this new Brushless technology brings to variable speed drives in general and Blow Molding Machines in particular. Areas specifically addressed include efficiency, accuracy, power factor, size, harmonics, and speed range. A basic description of how Brushless D.C. works and a comparison to other types of variable speed is given. With increasing emphasis on product quality at lower costs, the need for modernizing the Blow Molding Machine becomes ever more important.

I. INTRODUCTION

The first variable speed drives were certainly mechanical and were based on adjustable pitch diameter pulleys. Such systems are still in use but for obvious reasons are not in general uses in industrial applications today. There are four basic types of electrically adjustable speed drives being installed in today's modern industrial machines:

- DC Brush type motors and controllers
- DC Brushless motors and controllers
- AC Variable frequency controllers and induction motors
- AC Vector controllers and induction motors

Historically, the brush type DC motor has been nearly the exclusively used variable speed drive on blow molding machines. The use of AC variable frequency and AC vector drives on blow molding machines has been almost nil and will not be covered in this paper [1]. A rather unique type of brush motor called a brush shifter was popular on early machines. The Brush rigging was moved mechanically by a small servo motor to control the speed. Electronically it was quite simple but the motor itself was quite complicated to manufacture and repair and most of the machines using such motors in the US have had the motors replaced by conventional brush DC machines with speed changed by the use of a thyristor controlled armature voltage controller. The Brushless DC drive can be a direct replacement for the brush DC drive and is the subject of this paper.

II. HISTORY OF BRUSH TYPE DC DRIVES

The brush DC motor was invented in 1856 by Werner Von Siemens in Germany. Variable speed by armature voltage control was first used in the early 1930s using a system involving a constant speed AC motor driving a DC generator. The generator's DC output was varied using a rheostat to vary the field excitation and the resulting variable voltage DC was used to power the armature circuit of another DC machine used as a motor. This system was called a Ward-Leonard system after the two people credited with its development. The Ward-Leonard method of DC variable speed control continued until the late 1960s when Electric Regulator Company brought to market a practical, general purpose, static, solid state controller that converted the AC line directly to rectified DC using SCR (thyristor) devices. That technology was adopted by virtually all manufacturers and still is in use today. It is a very simple power control concept and uses the fewest number of parts possible to produce variable speed from an electric motor.

III. CHARACTERISTICS OF DC DRIVES

The DC motor works on the principle that speed of the shaft is a direct function of the applied armature voltage. To a lesser extent, field control can be used for speed control but it is not widely used except for winders and constant HP applications and will not be discussed here. At zero volts applied to the armature, the motor will run at zero speed, while at rated voltage (500 vdc for most industrial motors over a few hp), the motor will run at rated speed (1750 rpm has developed as a "standard"). The motor will produce torque based on a similar relationship with current. The torque produced by a DC motor will vary directly with armature current. These two simple characteristics make the DC motor continue to be the most popular means of variable speed control in use today for constant torque industrial applications. DC motors are very efficient in converting electrical energy to mechanical energy with typical values of 90 to 92% for sizes from 10 to 75 hp. Controller efficiency is very high and averages 98% making the overall Efficiency 88 to 90% for the range of 5 to 75 HP. Unfortunately, the SCR, while being an efficient power conversion device, does so by varying the point on the AC voltage waveform at which current begins to flow. This means at mid- to low-output voltages, the power factor at which the power is used is very low [5].

While some years ago, this was not such a cause for concern, power companies are becoming more insistent that industrial users keep power factors up to at least .8 or higher. There are selfish reasons for the industrial user to keep power factors high as well since it reduces the size of transformers, breakers, fuses, and conductors in the power system. See the summary section on power factor.

IV. HISTORY OF BRUSHLESS D.C.

The earliest evidence of a Brushless DC motor was in 1962 when T.G. Wilson and P.H. Trickey made a "DC Machine with Solid State Commutation". It was subsequently developed as a high torque, high response drive for specialty applications such as tape and disk drives for computers, robotics and positioning systems, and in aircraft where brush wear was intolerable due to low humidity.

Unfortunately, the technology to make such a motor practical for industrial use over 5 hp simply did not exist until a number of years later. With the advent of powerful and permanent magnet materials and high-power, high-voltage transistors in the early to mid 80s the ability to make such a motor practical became a reality. The first large Brushless DC motors (50 hp or more) were designed by Robert E. Lordo at POWERTEC Industrial Corporation in the late 1980s. Today, almost all of the major motor manufacturers make Brushless DC motors in at least some horsepower sizes and POWERTEC makes Brushless DC from 1/2 to 300 hp as a complete product line.

Brushless DC has had a substantial impact in some industry market areas, primarily Plastics and Fibers, and most recently a mining company has put several of these drives at 300 hp ratings operating coal conveyors in underground mines. The drives work on the same principle as all DC motors but the motor is built "inside out" with the fields (which are permanent magnets) on the shaft of the motor and the "armature" on the outside. The fields turn and the "armature" stays stationary. To duplicate the action of the commutator (which no longer needs to exist since the winding is now stationary), a magnetic encoder is mounted to the shaft of the motor to sense the magnetic position of the fields on the shaft. The controller "sees" the magnetic position information and determines through simple logic which motor lead should have current going to a winding and which motor lead should return the current from the winding. The controller has power devices which connect the voltage on a capacitor bank to the correct motor lead at the correct time when the shaft encoder demands it. In this way, the motor and controller act in the same way as a brush DC motor but without the brushes. The controller is built in a very similar way to the controller used in an AC variable frequency drive or in an AC Vector drive because all three types use a PWM type of variable voltage control to their respective motors.

V. BRUSHLESS DC CHARACTERISTICS

Voltage on the motor determines speed and current in the motor determines torque. These relationships are linear and nearly identical to a standard Brush DC drive. The application of the product then is essentially like the more familiar brush machine. Speed accuracy is very high, in fact with the most widely used Brushless drive, the accuracy is synchronous (0% speed error) due to a digital encoder and drive controller position regulation. Torque to inertia ratios are very high providing high accel/decel rates and excellent dynamic response. Controller bandwidth (30 to 40 Hz) is 5 to 8 times higher [7] than the Brush DC drive.

Motor thermal characteristics is the major advantage of Brushless DC in that a thermal speed range of 100 to 1 at full rated torque is available on the standard motor and totally enclosed motors are available in very small frame sizes. Motor efficiencies range from 90 to 96% and controller efficiency is 97% giving overall efficiencies better than brush DC systems.

VI. BLOWMOLDING APPLICATIONS ADVANTAGES

In general, the characteristics of Brushless DC that are most advantageous to the blow molding process are:

- Very precise average speed control over a very wide speed range.
- Precise instantaneous speed control due to high dynamic response
- Constant power factor means lowest possible input current.
- Small physical size of motor compared to brush type.
- No recurring motor maintenance (brush replacement)
- Feedback device (encoder) is inside the motor not outside.
- Higher efficiency overall.

The blow molding process always involves an extruder of some kind and the variable speed drive on the extruder has to provide an output sufficient to allow the parison to be formed in time to meet the cycle requirements. Since the final product may require more or less volume of plastic for different shapes and because the cycle time varies, hence the requirement for variable speed. The result of inconsistent speed control is simply that more (or less!) material than is necessary to make the part will be extruded. Speed control consistency, therefore, is important to the production of a consistent product.

Speed that either drifts slowly from the setpoint speed over a long period of time, or speed that changes rapidly as a function of load, line voltage, AC line voltage, and/or other effects changes the process and ultimately either affects product quality or waste.

In the cases where rotary (wheel type) molds are used, the wheel drive must be coordinated with the extruder so the parison is the right size when the mold is ready to clamp. If the average rotational speed of the wheel is incorrect, the result is the same as if the extruder were running the wrong speed since the relationship of parison size to mold position would be off. One factor not necessarily considered however, is that even though the average rotational speed may be correct, the instantaneous speed of the wheel may be varying substantially. This is due to the fact that the torque loads seen by the motor vary as a function of the angular position of the wheel since the wheel operates the mold opening and closing cams. This reciprocating load will cause problems with some parts because it will directly affect the instantaneous speed of the wheel and therefore the "timing" of mold close and release relative to the parison formation. At least two blowmolding manufacturers have looked at this effect and the results are as follows.

Machine A: Machine had 12 stations making a large bottle. The machine was geared for approximately 80 bottles per minute at a motor speed of 1750 rpm. One test was run with a brush type DC motor and conventional Thyristor controller with tachometer feedback. Using a stroboscope synchronized the average speed of the motor shaft, the variation in the motor shaft position as the cam loading occurred could be observed. A shift of something between 180 degrees and 270 degrees of motor shaft rotation could be observed at every mold closing point. The average speed was also being affected causing a "drift" from the reference shaft position. See figure [1]. The brush drive was then removed and a Brushless DC drive was installed on the same machine and the tests were repeated. This time the change in shaft angle at the motor was approximately 18 to 20 degrees at every mold closing point and there was no change in the reference position. In other words the shaft average speed was being held synchronous to the set speed in the average sense and within 18 to 20 degrees in the instantaneous sense.

To explore the potential accuracy further, an external, high count (600 ppr) encoder was added to the Brushless DC drive and the test was repeated. This time the shaft angle change with load was less than 4 degrees! The relationship of motor shaft angle to the wheel angle is 360 degrees of motor rotation equals 16 degrees of the wheel. This relates to approximately 0.056" of circumference of the wheel at its largest diameter per degree of motor shaft rotation. Table 1 shows these data.

DRIVE TYPE	FEEDBACK DEGREES		ERROR AT DIAMETER
Brush D.C.	tach gen	180 degrees	10"
Brushless D.C.	120 ppr	18 degrees	1"
Brushless D.C.	600 ppr	4 degrees	.25"

TABLE 1: CIRCUMFERENCE ERROR DUE TO LOAD

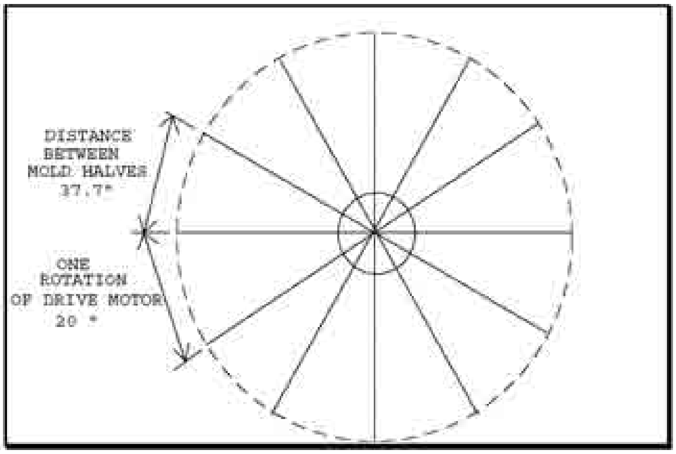


Figure 1. Wheel Mold

Machine B: A machine by another manufacturer has a very large diameter wheel measuring 108" in diameter. 1750 rpm equals 6 rpm of the wheel. The wheel has 12 stations. An investigation to determine the best drive to minimize any instantaneous or average speed change was made and both brush type DC as well as AC type drives were used. The manufacturer settled on a Brushless DC drive. The final results of a stroboscopic study showed that the ring gear with a 108" pitch diameter with 3-pitch teeth (.33 in/tooth) did not vary either in long term average or instantaneous position by more than 1 tooth. Variations of several inches were noted with other drive types.

VII. POWER FACTOR

In addition to the speed regulation and dynamic response characteristics of Brushless DC, the efficiency and power factor can be major considerations. Efficiency differences are not dramatic since brush D.C. is already a high efficiency technology. Since the differences are small (about 2%), the potential savings due strictly to efficiency are not great taken by themselves except on large machines or a large number of smaller machines. Power factor differences however are very large and the potential savings due to the combination of efficiency and power factor can be quite large since blowmolding machines typically run 24 hours a day, seven days a week.

Power factor is a term recently being given a considerable amount of press, primarily due to the increased pressure by utilities on users to improve the operating power factors of industrial plants. Closely related to power factor is a harmonic current. Both of these are becoming very important terms because of penalties, extra charges, and outright refusal to allow connection to AC power sources unless controlled within certain parameters.

Power factor is a measure of how much real current is required to operate a certain load (usually inductive) relative to the current to operate the same load if it were a pure electrical resistance [5,6]. It is defined as the ratio of real power (watts) to apparent power (KVA). As an example, if a machine required 100 amperes to operate with a perfect power factor (1.0, pure resistive load), the same machine would draw 200 amperes to do the same work if the power factor were .5. While the watts are the same in both cases, and the power meter would read the same in both cases, a demand meter or power factor meter would see the difference and the power company would obviously rather deliver the 100 amps than the 200 amps at the same cost! It matters to the user however, even if the power company doesn't care because a transformer, for instance (same for switch gear, fuses, wire, etc.) would have to be twice as large for the poor power factor machine. Usually directly associated with this problem is a companion problem involving harmonic currents. When AC current is drawn from the line in other than a sinusoidal waveform, harmonic currents result that cause significant power losses and disruptive effects on the power source [6]. Large harmonic currents cause both the user and the utility problems and should be avoided when possible.

Brush type D.C. drives create both low power factor and high current harmonics due to the way in which power is converted. Little can be done, within practical cost constraints to prevent it. DC Brushless drives use power control circuitry involving a full wave diode bridge, capacitors, and output switches. A key item in the design relative to both power factor and reduced harmonic currents is the choke which is shown as a option in the diagram below. This choke must be fairly large (in the range of 2 to 5 millihenries) to have the best effect and some kind of choke must be present [5] or the resulting power factor and harmonic current draw can be even higher than the brush type drive at some speeds and loads. The user should take care to insure that an appropriately sized choke is provided in the equipment design he is considering since the use of such a choke is not widespread. These chokes add a measurable cost to the equipment and since it is not necessary to operation, there is significant pressure on the equipment supplier to not include the choke in the design. Be aware that this choke, in order to be effective in increasing power factor MUST BE DOWNSTREAM OF THE DIODE BRIDGE, [6]. It will not work when added to the AC input side and, therefore, must be bought built into the equipment.

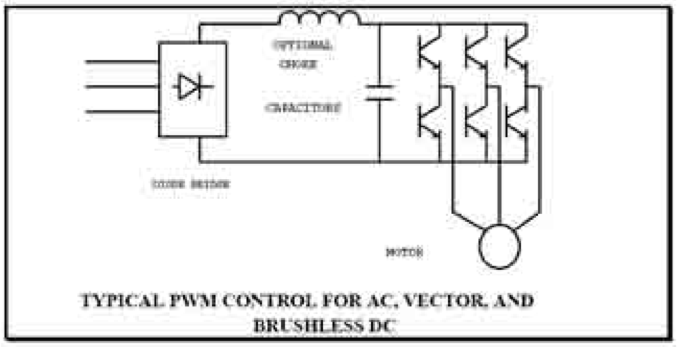
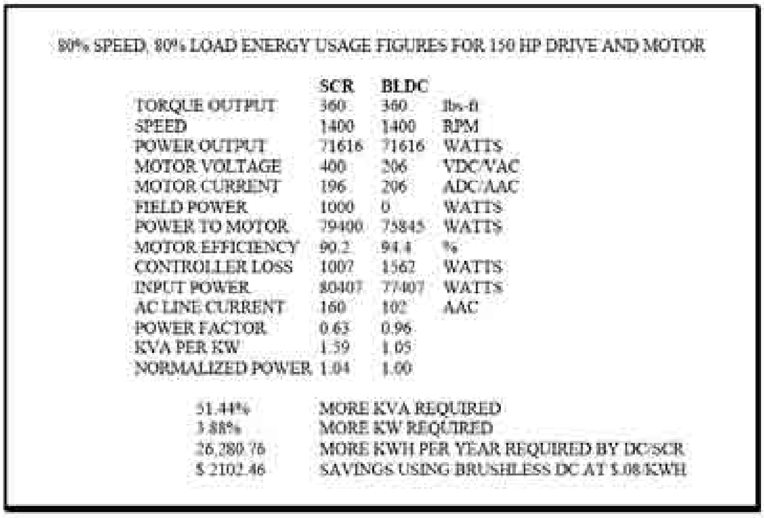


Figure 2. Choke location in power bridge

Table 2 shows the result of calculations involving a typical extruder running at 80 of rated load and 80% rated speed (a common operating condition) continuously using a brush type drive versus a Brushless DC drive with the appropriate buss choke. The figures are based on a 150 hp drive.



80% SPEED, 80% LOAD ENERGY USAGE FIGURES FOR 150 HP DRIVE AND MOTOR

	SCR	BLDC	
TORQUE OUTPUT	360	360	lbs-ft
SPEED	1400	1400	RPM
POWER OUTPUT	71616	71616	WATTS
MOTOR VOLTAGE	400	206	VDC/VAC
MOTOR CURRENT	196	206	ADC/AAC
FIELD POWER	1000	0	WATTS
POWER TO MOTOR	79400	75845	WATTS
MOTOR EFFICIENCY	90.2	94.4	%
CONTROLLER LOSS	1007	1562	WATTS
INPUT POWER	80407	77407	WATTS
AC LINE CURRENT	160	102	AAC
POWER FACTOR	0.63	0.96	
KVA PER KW	1.59	1.05	
NORMALIZED POWER	1.04	1.00	

51.44%	MORE KVA REQUIRED
3.88%	MORE KW REQUIRED
26,280.76	MORE KWH PER YEAR REQUIRED BY DC/SCR
$ 2102.46	SAVINGS USING BRUSHLESS DC AT $.08/KWH

TABLE 2: Efficiency Comparison brush DC to Brushless DC

The dollar savings above are figured based only on the efficiency differences and do not account for the power factor related savings due to extra losses in wire, transformers, etc. which add another $1000 per year, and that does not include any penalties or correction costs for poor power factor. A detailed derivation of these numbers is not included here but can be obtained from POWERTEC Industrial Corporation. See the references at the end of this paper [8].

VIII. SUMMARY AND CONCLUSIONS

While there are several options available to the manufacturer and user regarding the type of variable speed drive to use on the Extruder and rotating mold applications of the blow molding machine, there are some distinct advantages in the use of the Brushless DC drive. While other types of drives may become available in the future that may provide these advantages, they are not yet available for general use in the HP sizes necessary for most blow molding machines. The Brushless DC technology is here and in wide use in various extrusion and related applications in the plastics industry.

IX. REFERENCES

[1] T.G. Wilson, P.H. Trickey, "D.C. Machine With Solid State Commutation", AIEE paper #CP62-1372, Oct 7, 1962.

[2] NEMA Publication #MG 1, ref MG-1.41.2, table 12.6B

[3] Eaton Dynamatic Electric Drive Applications Guide page M-37.

[4] Dennis P. Connors, Dennis A. Jarc, Roger H. Daugherty, "Considerations in Applying Induction Motors with Solid-State Adjustable Frequency Controllers", IEEE Transactions on Industry Applications, Vol 1A-20, no. 1, January/February 1984.

[5] John B. Mitchell, "Inverter Power Factor and Noise", Power Transmission Design magazine, page 45, 46.

[6] Derek A. Paice, "Harmonic Issues and Clean Power Controllers", Westinghouse Electric Corp, Presented at PCIM '90, Oct 25, 1990.

[7] Frank J. Bartos, "Reliability, Ease of Use Widen AC Drives' Application Horizons", Control Engineering News, page 55, February 1992.

[8] Robert E. Lordo, "Comparison of the 150 HP Brushless DC and conventional DC/SCR motor/Control", June, 1992, POWERTEC Industrial Corp. Box 2650, Rock Hill, S.C. 29732, phone 803-328-1888.

USE OF VARIABLE FREQUENCY DRIVES FOR FAN AND PUMP CONTROL

Natural Resources Canada

DESCRIPTION

In the past 10 years, variable speed control for fans, pumps, chillers and HVAC systems has become an affordable way to save energy, thanks to advances in microelectronics and control technology. Initially, utility companies introduced incentives to make it practical to switch from fixed speed and flow-throttling controls to variable frequency drives (VFDs) (Figure 1).

Since then, more building designs have been specifying VFDs, and many building HVAC retrofits can become more cost-effective by replacing flow controls with VFDs at installed costs as low as $250 per kilowatt. Naturally, the process must be carefully studied to ensure that the application will be successful.

Figure 1. Typical Variable Frequency Drive Control Panel

TECHNICAL SPECIFICATIONS

Drive Specification – VFDs operate by converting the incoming AC power to a DC signal and then re-transmitting the power signal to the motor at varying frequencies and voltages. VFDs can operate rotating equipment at speeds ranging from nearly 0 RPM to as high as 150 percent of the rated speed for the motor. The use of a frequency drive requires installing high-efficiency Class F insulated motors that can withstand the variations in voltage and current flux.

Applications – Some good applications include 1) replacing outlet dampers or variable inlet vanes (VIVs) in supply fan systems controlling variable air volume (VAV) boxes; 2) controlling air supply to multiple zones by adding a VFD and isolation dampers in zones with different occupancy and operating schedules; and 3) controlling pump speed by maintaining a pressure setpoint. Other advantages of variable frequency drives include less wear on the motor due to reduced speed and torque, gentler starting through gradual acceleration, and fewer moving parts (i.e., no damper or inlet vanes to wear out). Figure 2 shows a typical fan application requiring two VFDs with pressure control feedback.

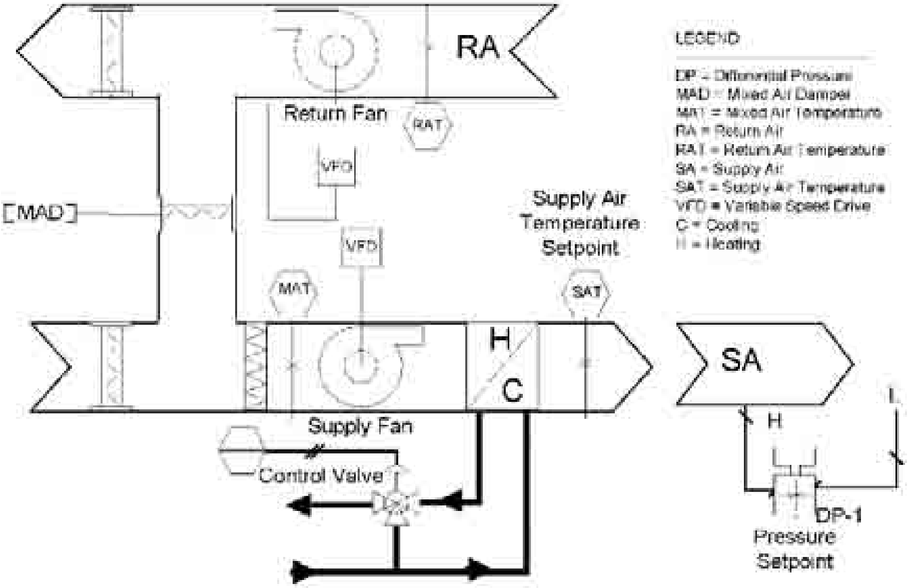


Figure 2. Schematic of VFD Installation

ENERGY INFORMATION

The real energy savings from variable frequency drives come from the basic laws of fan and pump operation. Theoretically, fan power input will drop according to the cube of the flow rate (load). This is illustrated in the equation below:

$$W_2=W_1\times(Q_2/Q_1)^3$$

As an example, if the Power (W1) is at 100 percent flow (Q1) and the flow is reduced to 80 percent, the new Power (W2) will be W1 __(0.8)3 = 0.51 or 51 percent.

When a fan is throttled back by an inlet vane, the power drops along with the flow rate to a certain value. However, the poor inlet or outlet conditions cause fan performance to suffer, motor efficiency drops as the load is removed, and power savings are reduced (Figure 3). In the case of a VFD, the motor and fan speed are reduced and the losses are much smaller, approaching that of the ideal case.

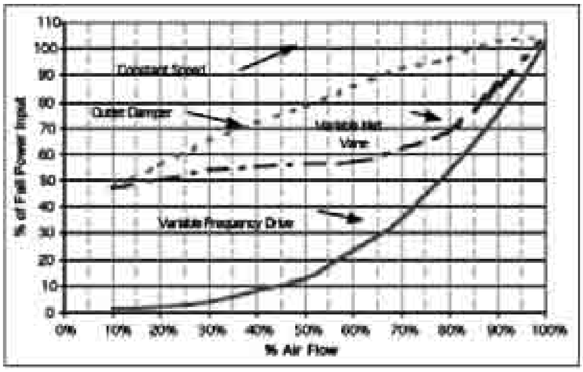


Figure 3. Energy Comparison

COMPARISON

Figure 3 illustrates the difference in power consumption of a typical VFD compared to three common retrofit applications, including VIV control, outlet damper control and constant speed. To estimate the energy savings from a VFD installation, the duty cycle of the equipment must be established. For example, if a fan system was off for eight hours per day, and operated for eight hours at 50 percent flow, six hours at 80 percent flow and two hours at 100 percent flow, the power saving from VFD control would be 40 percent over an inlet vane and 55 percent over outlet damper control.

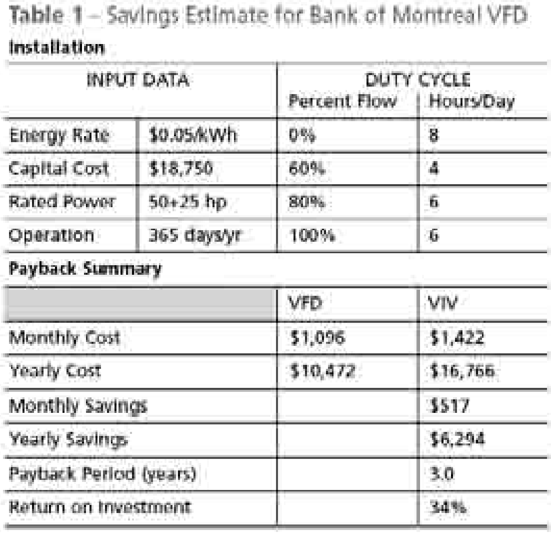


Table 1 – Savings Estimate for Bank of Montreal VFD

Installation

INPUT DATA		DUTY CYCLE	
		Percent Flow	Hours/Day
Energy Rate	$0.05/kWh	0%	8
Capital Cost	$18,750	60%	4
Rated Power	50+25 hp	80%	6
Operation	365 days/yr	100%	6

Payback Summary

	VFD	VIV
Monthly Cost	$1,096	$1,422
Yearly Cost	$10,472	$16,766
Monthly Savings		$517
Yearly Savings		$6,294
Payback Period (years)		3.0
Return on Investment		34%

CASE STUDY

In 1997, a Bank of Montreal building in Vancouver, British Columbia retrofitted its HVAC systems as part of a building upgrade. The building's previous main air system consisted of a 75-hp supply fan and a 40-hp return fan, which provided air for variable and constant volume mixing, and heating boxes that provided heating and cooling to various zones. The fan was fitted with VIVs, which modulated to maintain the pressure in the system. The retrofit consisted of replacing the fan motors with a 50-hp supply and a 25-hp return, and installing a variable frequency drive in place of the inlet vanes. Based on the 24-hour duty cycle of operation shown in Table 1, the new system saves an estimated $6,294 per year based on 1997 rates, with a simple payback period of three years.

EVAPORATOR FAN VARIABLE FREQUENCY DRIVE EFFECTS ON ENERGY AND FRUIT QUALITY

Robert D. Morton and Mike L. McDevitt, Cascade Energy Engineering

Our firm is at the 18-month point of a 2-year research project to investigate the energy and fruit quality benefits of evaporator fan variable frequency drives (VFDs) in controlled atmosphere (CA) rooms. During the 1998-1999 holding season, we conducted 10 comparative tests of evaporator fan VFDs in commercial CA rooms in Washington state. In each test, a room with fruit in bins and an evaporator fan VFD was compared to second room that used an alternate fan control strategy (baseline control). Depending on the site, the baseline fan control was continuous fan operation, alternating fan operation, or fan cycling. The field trials consistently showed that using VFD instead of alternate fan control resulted in excellent energy savings. Also, the tests showed that using VFD fan control reduced mass loss in every case.

This document provides:

- A brief background on evaporator fan VFDs
- A summary of our test methodology
- A list of assumptions regarding economic return on this technology based on our test findings
- Answers to frequently asked questions.

BASICS OF EVAPORATOR FAN VFDS

Evaporator fan VFDs are electronic motor controllers that can be used to reduce fan speed after fruit has been pulled down to storage temperatures. Collectively, the evaporator fans are usually the single largest electrical load in a CA facility during the long holding season. The VFDs offer very attractive energy savings. At half-fan speed, (which is typical during the holding season), the fans will consume only about 15% of full speed power.

TEST DESCRIPTION

Tests were conducted at 10 sites (commercial CA rooms) in Washington state. At each site, a VFD controlled room was compared to a baseline CA room that used existing fan control (continuous fan operation, alternating fan operation, or fan cycling). One major element of the testing involved placing fruit samples at 15 locations within each CA room as the rooms were filled. In order to minimize differences in the test fruit, all fruit was taken from a single bin from a single grower. Each fruit was weighed, numbered, and placed in a mesh bag (six or eight fruit to a bag, depending on the site). The sample bags were buried under one or two layers of fruit in the CA bins as the rooms were loaded. The bags were retrieved when the rooms were opened the following spring or summer. The fruit was re-weighed and then sent to the laboratory for testing. At some sites, this process was repeated for multiple growers.

Most room-to-room comparisons involved similar length holding seasons. Room loading and unloading were not identical in every case.

A total of 18 lots of fruit were tested at the 10 test sites, including Red Delicious apples (8 lots), Golden Delicious apples (9 lots), and Anjou pears (1 lot).

In addition to fruit quality testing, two sites included detailed monitoring of temperature (17 locations per room), dew point (one location per room), and real-time mass loss data from a load cell. A third site included measurement of carbon dioxide (CO2) and oxygen concentrations at high and low air movement locations within the room. These measurements were intended to provide insight regarding conditions within the room and their ultimate effect on fruit quality.

ECONOMIC ASSUMPTIONS

To put the results in context, we estimated energy and fruit savings for each field trial and return on investment.

Fruit savings were based on:

- The total fruit weight in the room
- The difference in percentage mass loss between the VFD room and the baseline control room
- An assumed 80% packout rate and $12 per box fruit value
- VFD cost estimates for large-scale installations.

THE ECONOMICS OF VFDS FOR CA STORAGE

What kind of payback should I expect?

- Paybacks for the field trials ranged from 1.1 to 2.9 years when energy savings and mass loss improvements were considered (Figure 1).
- Paybacks ranged from 1.6 to 21.6 years when only energy savings were considered (Figure 2).

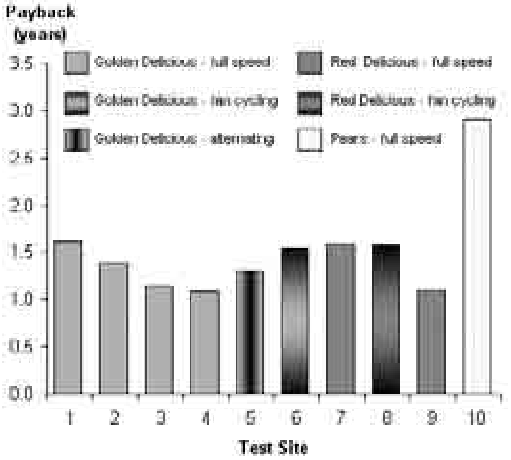


Figure 1. Payback on energy and mass loss savings using VFD control versus baseline control

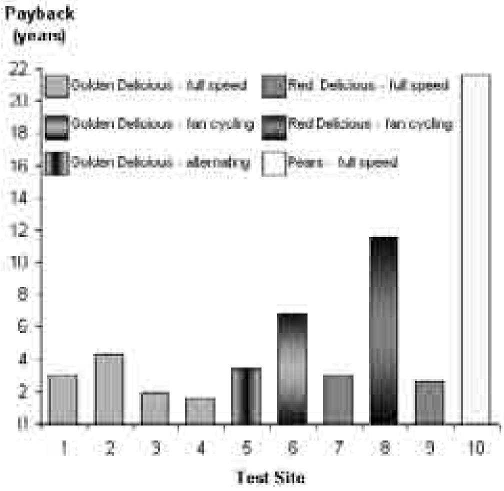


Figure 2. Payback on energy using VFD control versus baseline control

Why is there a large range of payacks?

- Paybacks were influenced by storage duration, baseline fan operations (full-speed, alternating, or cycling), mass loss, and utility rates.

When would I expect the fastest payback?

- Fast paybacks are characterized by having a full-speed fan baseline, long storage duration, and high cost electricity (test sites 3, 4, and 9).

When is a mass loss improvement with VFD operation important to project economics?

- When facilities have:
  - Low baseline fan energy use (fan cycling or alternating fans), such as test sites 5, 6, and 8.
  - Short storage duration - test site 10.
  - Low cost electricity - test sites 1, 2, 6, 7, and 10.

What rules of thumb would indicate if a CA room is a good candidate for VFD control?

- Any new construction.
- Long storage duration.
- Baseline of full speed fan operation.
- Located in an area with high cost electricity.

THE EFFECT OF VFDS ON BIN-STORED CA FRUIT QUALITY

Will using a VFD reduce product mass loss?

- YES! VFD operation produced lower average mass loss in all 18 tests involving 10 separate VFD installations (Figure 3).

How much mass loss improvement was seen?

- Mass loss savings ranged from 0.06% to 0.58%.

What fruits and varieties were tested?

- Golden Delicious apples (9 tests)
- Red Delicious apples (8 tests)
- Anjou pears (1 test)

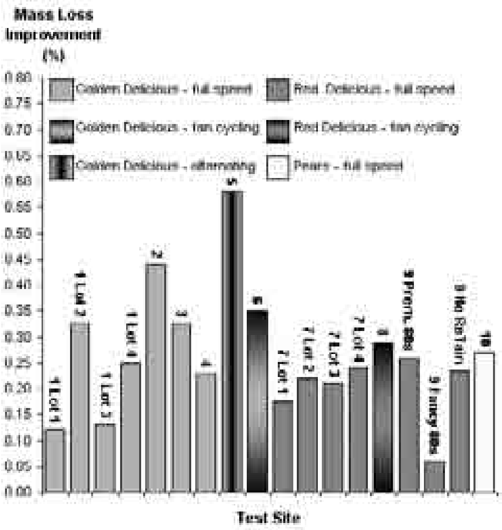


Figure 3. Mass loss improvement using VFD control versus baseline control

Where were the biggest mass loss improvements found?

- The biggest improvements in mass loss were found in Golden Delicious apples.
- An improvement of 0.27% was realized in the Anjou pear test during only ~50 days of reduced speed operation with the VFD.
- Tests with long holding periods.
- Tests where the baseline fan control was fan cycling or alternating fans.

What effect does VFD operation have on fruit firmness?

- Average fruit firmness decreased in 7 out 9 of the VFD tests on Golden Delicious apples (Figure 4).
- Average fruit firmness decreased in 4 out 8 of the VFD tests on Red Delicious apples.
- Average fruit firmness decreased in the one pear test.

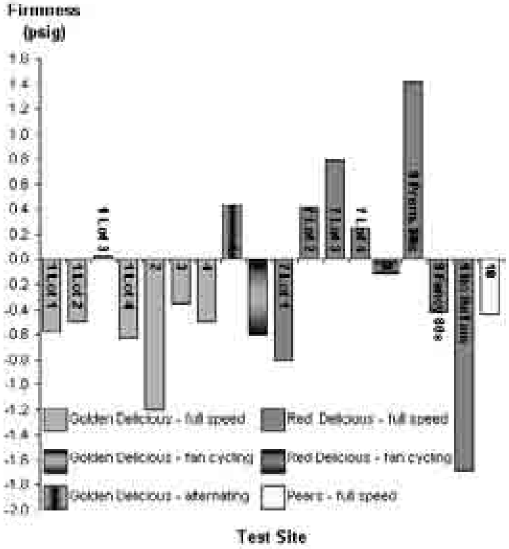


Figure 4. Change in fruit firmness with VFD control versus baseline control

Under what circumstances was the largest effect on fruit firmness observed?

- At test site 9, in the two tests where the firmness decreased with the VFD control, when the sample fruit was tested prior to storage it was deemed unsuitable for long-term CA storage.
- At test site 4, it was necessary extrapolate the change in firmness (the baseline control room opened 100 days after the VFD room). There is considerable room for error in the extrapolation.

RELIABLE AND ENERGY EFFICIENT VFD OPERATION

How much energy savings can be expected with VFD operation?

- In the field trials, energy savings varied from 24% to 78% (Figure 5).

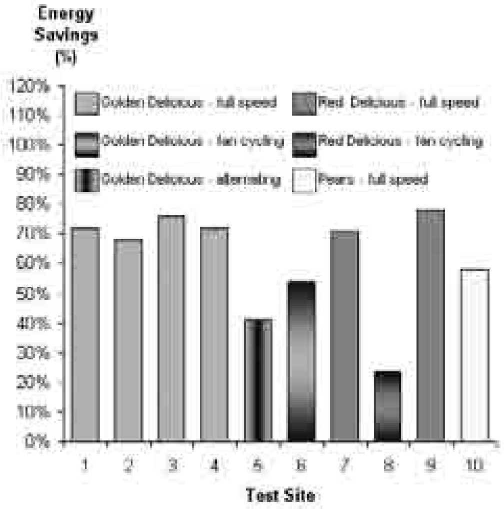


Figure 5. Energy savings using VFD control, shown as percent of baseline energy use

When were the largest energy savings achieved?

- At facilities that used full speed fans and had long storage periods.

When were the smallest energy savings achieved?

- At facilities that fan cycled or shed fans after the fruit pulldown (test sites 5, 6, and 8).

Can peak demand charges be reduced by using VFDs?

- With careful management, VFDs can significantly reduce peak demand charges.

Do VFDs affect fruit pulldown?

- The VFD has no impact as fan speed is not reduced during the fruit pulldown period.

When should fan speed be reduced with the VFD?

- After the fruit has been brought to room temperature.
- In the field trials, fan speed was reduced 3 to 4 weeks after the rooms were sealed.

How far should fan speed be reduced?

- In the field trials, the minimum fan speed was limited to 40% to 50% speed. Further reduction in speed would provide little additional savings.

THE EFFECT OF VFD OPERATIONS ON ROOM CONDITIONS

Will reducing fan speed produce warm spots in the room?

- No. Extensive temperature monitoring at two facilities showed no warm spots. Temperatures were monitored inside 15 bins distributed evenly in each test room.
- The warmest probe in the VFD rooms were only 0.03 °F and 0.16 °F warmer than the respective warmest control room probe (Figure 6).

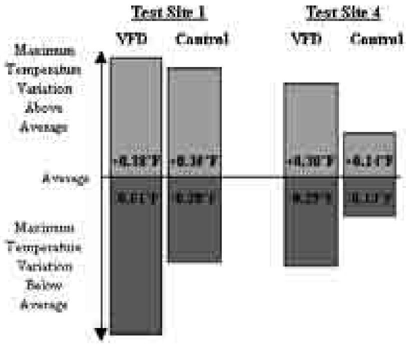


Figure 6. Temperature variance – VFD control versus alternate fan control at Test Sites 1 and 4

Will reducing fan speed produce cold spots in the room?

- At reduced speed, air comes off the coil colder than in a full speed room. As a result, colder temperatures were seen towards the top of the VFD rooms.
- The coldest probe in the VFD rooms were only 0.23 °F and 0.16 °F colder than the respective coldest control room probe (Figure 6).

How would you summarize the difference in temperature control between VFD and full speed operation?

- VFD operation resulted in a slightly higher variation in temperatures throughout the room. When comparing the VFD room versus the control room, the total average temperature variation for all 15 probes were 0.89 °F versus 0.63 °F and 0.59 °F versus 0.27 °F for the two tests.

Was there any evidence of CO2 buildup or any adverse impact on gas concentrations at reduced speed?

- No. At one facility, gas samples were obtained in the VFD room in a high air flow location (near the evaporator) and a low air flow location (within a bin in the back lower corner of the room). Gas concentrations in these two locations were practically identical, indicating that the air in the room was adequately mixed at reduced speed.

Did reducing speed increase the relative humidity or dew point temperature in the VFD room?

- Yes. The relative humidity was slightly higher in the VFD room at both test sites.

MEDIUM VOLTAGE DRIVES IN THE SUGAR INDUSTRY

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L.C. Krishnan, Al Khaleej Sugar Refinery, Dubai

ABSTRACT

This paper first outlines the benefits of Medium Voltage Variable Frequency Drives (MV-VFD) compared to classical drivers or control methods (i.e. steam/gas turbines, hydraulic coupling and Direct- On-Line operation with, for example, valve/damper control).

The paper then focuses on typical variable frequency drive applications in the sugar industry and also describes two real cases, namely a MVVFD soft-starter application at Al Khaleej Sugar Refinery, Dubai, UAE and the replacement of inefficient steam turbines for cane mill drives at Compania Azucarera Hondurena S.A, Honduras, Central America.

Next, the main selection criteria for a MV-VFD system are described and finally a state-of-the-art example of such a product complying with the above-described selection criteria will be presented.

I. INTRODUCTION

A. WHAT IS A VARIABLE FREQUENCY DRIVE?

A VFD is basically an electrical circuit, which is connected between a supplying network and a motor. Unlike a Direct-On-Line (DOL) operated motor, the speed of which is fixed to the frequency of the supplying AC network, the main purpose of a VFD is to provide the motor with an AC supply voltage (or AC current) of variable frequency, enabling a variable motor speed and torque.

In general, a state-of-the-art VFD consists of a rectifier section, a DC-link section and an inverter section. The rectifier section rectifies the supplying AC network voltage of fixed frequency (usually 50 or 60Hz) into a DC voltage (or DC current), which then, in the inverter section of the VFD, will be transformed into an AC voltage (or AC current) of variable amplitude and frequency, see also Fig.1.

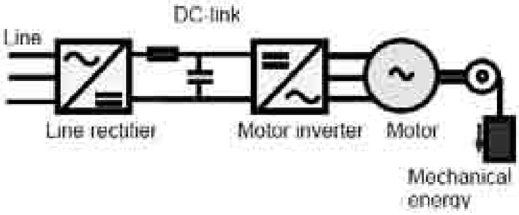


Figure 1. Basic components of a VFD

When talking about Variable Frequency Drives (VFDs), one has to distinguish between Low-Voltage (LV) VFDs (up to 690V motor voltage) and Medium-Voltage (MV) VFDs (above 1kV motor voltage). Typically the economically reasonable power range for LV-VFDs is about 0...1000Hp, whereas MV-VFDs start to become economical from about 500 Hp up to more than 100 000 Hp.

This paper is focusing on MV-VFDs although a lot of the statements made can also be applied for LVVFDs.

B. SHORT HISTORY OF MV-VFDS

MV-VFDs were introduced into the market in the late ‘60s. The benefits of MV-VFDs in those days were basically the same as today (e.g. energy savings, improved process control, less maintenance…). However these benefits were, to some extent, compensated by drawbacks such as power factor issues, harmonic distortion, torque pulsations and, maybe worst of all, reliability problems.

These problems have now been basically eliminated, allowing the advantages of a MV-VFD system to clearly dominate.

This opened the doors for MV-VFDs in many industries such as oil & gas (see [1]), petrochemical, power, water & waste water, metals, minerals & mining, marine, to name just a few, mainly for the controlled and economical transport of liquids, gas and solids.

C. MV-VFDS IN THE SUGAR INDUSTRY

In the sugar industry, a lot of applications are suited for operation with a MV-VFD instead of the conventional driving methods (e.g. gas or steam turbines, damper/throttle-, vane-, On/Off- or pitch control).

Besides a short description of the benefits of a MVVFD system, this paper is also dedicated to giving an overview of the processes where MV-VFDs will result in remarkable advantages for the customer. Furthermore, it will give some basic guidelines for the selection of such a MV-VFD system.

II. BENEFITS OF MV-VFD SYSTEMS

A. ENERGY SAVINGS

VFDs offer a wide range of benefits such as improving the quality of a product by having a better control of the process and, due to an optimal pressure or flow control, substantial energy savings.

Where are these energy savings coming from? As an example, we assume a Direct-On-Line (DOL), also called fixed speed motor, driving a pump. An electrical motor, which is directly connected to the power grid, will operate at a fixed speed, which is defined by the network frequency and the motor pole number. Therefore, the connected load machine is always rotating at the same speed.

The process requirements however may change, depending on various factors such as change in production quantity or quality, change of the media or deviations from the nominal power grid parameters (change in frequency), varying temperatures or simply new requirements such as production increase. These changes in process requirements also require control actions in the driving system.

The only possible control methods for fixed speed solutions are throttling, bypass control, On/Off control or the upgrade with a VFD solution, see Fig. 2.

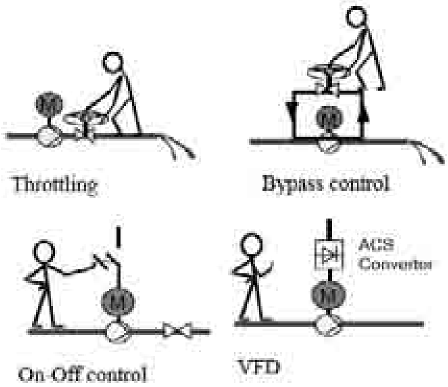


Figure 2. Examples of fluid control

The least efficient control method is the bypass control followed by the On/Off control. With bypass control, the superfluous flow is redirected back to the pump via the bypass valve. With On/Off control, the system is switched on and off depending on the actual flow or level requirement. This control method is often used in applications where a certain fluid level or capacity is controlled.

The control method usually used for fixed speed operation is throttling where opening or closing a valve controls the flow. Depending on the valve position the motor has to work against the valve. This results in a waste of energy and higher maintenance cost. The use of a VFD is the optimal, most energy-efficient control method which ensures that only the energy which is required by the driven mechanical load will be consumed. The VFD system losses are comparably low.

For a summary of the different control methods in regard to their efficiency, see also Fig. 3.

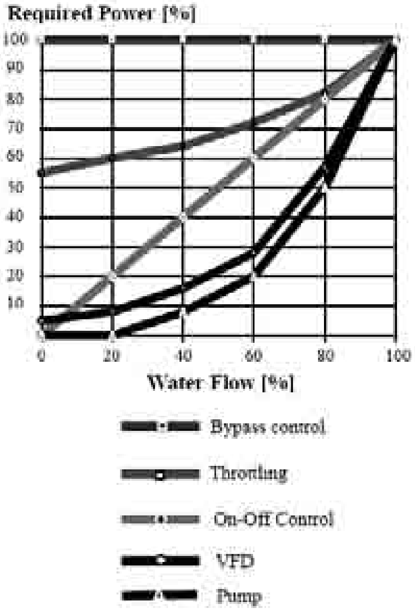


Figure 3. Comparison of different pump control methods in regard to their efficiency

In order to calculate potential energy savings in a convenient way, ABB has developed two easy-to-use programs, named PumpSave and FanSave. These tools calculate, based on some basic inputs, the estimated energy savings and payback times for a specific pump and fan application. The programs are based on Microsoft Excel® and are available free of charge from ABB MV drives.

Calculations typically result in payback times for a VFD investment between 1.5 to 4 years, mainly depending on the load cycle and the energy costs. Fig. 4 shows the input data mask of the PumpSave tool.

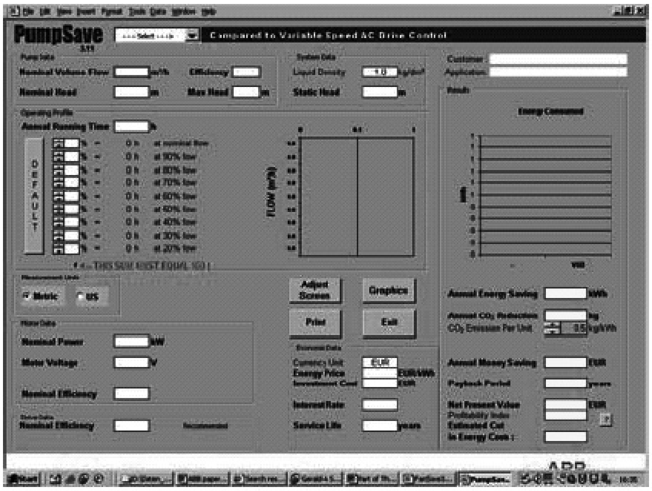


Figure 4. Input data mask of ABB's PumpSave Tool

B. MINIMIZED MAINTENANCE

By replacing mechanical components such as valves, dampers and gas/steam turbines with electrical equipment, i.e. a MV-VFD system, the maintenance efforts will be minimized. A reliable and well-designed VFD system will, with a minimum of maintenance, not require any major component replacements within the first 10+ years.

The only components requiring a yearly check are, for example, back-up batteries, deionizer vessels (in water-cooled VFDs) or air filters (in air-cooled VFDs).

Although it is recommended to have a regular maintenance schedule, many of these checks can be done while the drive system is in operation, which will avoid a process shutdown.

C. IMPROVED PROCESS CONTROL PERFORMANCE

Compared to mechanical solutions such as damper/throttle, vane, On/Off or pitch control, MV-VFDs provide a much smoother and more accurate way of controlling a process.

With a MV-VFD system, speed and torque can be adjusted and maintained with accuracies of 0.1% and better. As a result, depending on the application, the process is controlled in a more efficient way and the process output is of better quality.

Other benefits include a lower system noise level and the integrated motor protection equipment, which is part of the VFD scope of supply. At DOL operation the motor protection equipment has to be supplied separately.

D. EXTENDED LIFETIME OF MOTOR AND MECHANICAL EQUIPMENT

Due to the smooth, soft-start capabilities and wide range of adjustable speed and torque control capabilities of a MV-VFD system, the lifetime of the motor and the driven mechanical equipment will be extended.

For example, due to the reduced pressure at partial load, the lifetime of pipes and other components is increased. By applying a VFD system, vibrations can be reduced which increases the lifetime of the equipment.

E. ELIMINATION OF MOTOR INRUSH CURRENTS

With a MV-VFD system, the high inrush currents during start-up, which typically can exceed 5-7 times of the nominal motor current, will be eliminated. Especially in applications with high inertias (e.g. fans), high inrush currents may result in a considerable overdesign of the motor due to the extended acceleration times at high inrush currents, which increases the price of the motor. With a MV-VFD system, the start-up is extremely soft, and the currents on both the line supply side and the motor side will not exceed their nominal values during start-up.

It should be stressed at this point that a start-up with a so-called soft-starter would not result in the same low motor current values as in a start-up with a VFD system. Although significantly reduced compared to DOL starting, the inrush currents still remarkably exceed he nominal motor current values when soft-starters are applied.

F. ELIMINATION OF VOLTAGE SAGS DURING MOTOR START-UP

The start-up of a motor connected Direct-On-Line (DOL) typically comes with high inrush currents as pointed out in the previous paragraph. These currents are mainly of an inductive nature and therefore will cause a remarkable voltage sag at the Point of Common Coupling (PCC) where the motor is connected and also at upstream and downstream PCCs. As a result, many other electrical loads connected to one of these PCCs can be severely disturbed and therefore malfunction.

Opposed to that, during the start-up of a motor which is controlled via a MV-VFD system, none or only negligible voltage drops will occur and no other electrical equipment in the plant will be negatively affected.

G. IMPROVED IMMUNITY AGAINST SUPPLY DISTURBANCES

Typically, disturbances in the supplying network such as

- transient spikes
- unbalance
- voltage dips lasting over a few cycles
- frequency deviations
- or, most severe, interrupts will have an impact on the performance of a DOL operated motor.

Especially voltage dips above a certain magnitude (typically >10%) will instantly result in a reduced output power or a complete loss of the driven process.

With a MV-VFD system, “ride through” capabilities will ensure that the process will not at all or to a reduced amount be affected by supply disturbances of the kind mentioned above.

This is achieved with a DC link which, as a part of the VFD system, decouples the motor side from the feeding supply side, as well as sophisticated motor control schemes.

Also a short circuit in a DOL-operated motor will have a remarkable negative impact on the supplying network. With a VFD between the network and the motor, these short circuits are handled by the VFD system in a very fast manner and will have a minimum impact on the supply system.

III. MV-VFD APPLICATIONS IN THE SUGAR INDUSTRY

A. PUMP APPLICATIONS

The sugar industry in particular uses pumps for transferring liquor with, (a) controlled flow rate, (b) controlled pressure, (c) controlled level in the vessel. Besides the transfer of liquor, pumps are also used in power generation to feed water to the boiler. Using VFDs for such applications contributes to very high energy saving potential, making it the most economical and efficient method available as of today.

B. CONVEYOR APPLICATIONS

VFDs can be used to control the speed and torque of belt conveyors, resulting in easy management and very precise control.

C. ID AND FD FAN APPLICATIONS

Sugar plants use boilers to generate high-pressure steam for electrical power generation and low pressure steam for heat exchangers. Since the steam consumption varies depending on the demand, the boiler has to accommodate this variation by controlling the fuel and air. In order for this to be achieved with better performance and remarkable energy savings, VFDs are used for the control of boiler Induced Draft (ID) and Forced Draft (FD) fans.

D. CENTRIFUGE APPLICATIONS

VFDs can also be applied in centrifuge applications being the heart of sugar refining – for the batch centrifugal speed control. In this application, the use of VFDs with common DC bus is also the most reliable and efficient control method, contributing to minimum electrical equipment installations, lowest energy consumption and almost negligible impact on the power grid.

IV. PROJECTS FOR MV-VFD APPLICATIONS IN THE SUGAR INDUSTRY

A. PROJECT 1: SOFT-START OF MECHANICAL VAPOR COMPRESSORS WITH MV-VFDS

Al Khaleej Sugar in Dubai, UAE has been using VFDs for all previously-mentioned applications for the past ten years.

The installation of Mechanical Vapor Compressors (MVR) to reuse waste vapor is the latest ongoing innovative proj-

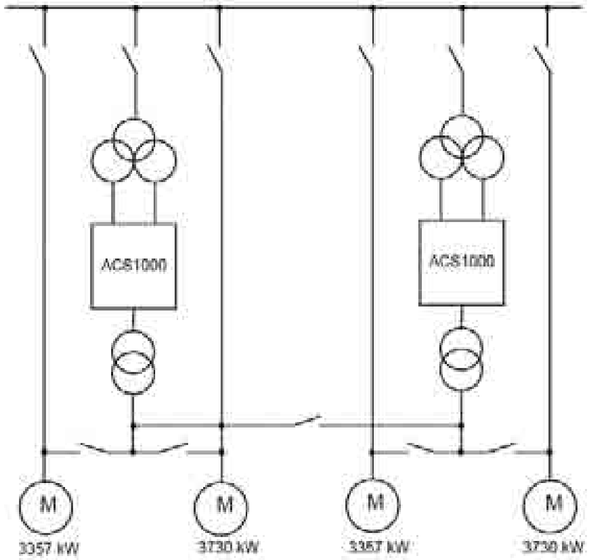


Figure 5. Basic one-line diagram of the electrical equipment at Al Khaleej Sugar for soft start of mechanical vapor compressors

ect at Al Khaleej Sugar. Two air-cooled ACS 1000 MV-VFDs from ABB are used as a softstarting device for four 4000kW motors and associated compressors with very high inertia, without any impact to the power supply grid, such as inrush current, voltage dips etc. For more information on ABB's ACS 1000 VFD family, the reader is referred to chapter VI of this paper.

In this specific application, the starting sequence can be sub-divided into three phases. In the first phase, a selected motor is smoothly accelerated with the MV-VFD from standstill up to nominal speed. This is followed by the second phase, in which the motors are synchronized with the supply network. Once the synchronization is completed, the motors will then, in the third phase, be bumplessly transferred to the grid. Due to the fact that the start-up and transfer is performed at low compressor load, the MV-VFDs can also be designed for a lower power rating. The basic one-line diagram in Fig. 5 illustrates the equipment line-up.

At present, only a few benefits of a MV-VFD system are utilized in this application. However, in case the mechanical vapor compressor application proves to be a successful innovation, it is planned to upgrade the installation with MV-VFDs that are rated for the full motor power in order to fully control the process with MV-VFDs. The additional benefits of such a system, in particular energy savings, can then be fully exploited. For further information about the mechanical vapor compressor project at Al Khaleej Sugar, the reader is referred to Fig. 15 and Fig. 16 in the appendix and to [6].

B. PROJECT 2: CANE MILLS

Compania Azucarera Hondurena S.A., founded in 1938, is one of the largest sugar companies in Honduras, Central America. Their Santa Matilde plant has a capacity of 10,200 tons/day (of cane) operating 155 days per year. In 2006 they expect to increase their capacity to 12,000 tons of cane per day.

In order to generate electric energy, the plant produces steam by combustion of bagasse, which is the principal waste product from sugar production. Part of the steam is used to run steam turbines which, in turn, drive cane-crushing mills. The rest of the steam is used to generate electricity for use by the factory.

Under normal operating conditions, there is sufficient steam to drive the cane mill turbines and to generate electricity for the plant. The cost of electricity in Honduras is relatively high because it is mainly produced by fuel oil. Thus the opportunity to optimize the energy use in the plant to be able to deliver more energy to the grid becomes very attractive.

Therefore, at their Santa Matilde plant, Compania Azucarera Hondurena S.A. replaced five steam turbines which were driving the cane mill, with ACS 1000 variable speed drives and induction motors. By controlling the cane mill with these drives and electrical motors instead of steam turbines, the steam can now be used exclusively to generate electricity, which will feed the whole plant and can even be sold to the grid.

Now, what does this mean in real numbers? In the case of this particular plant, five 750kW steam turbines are needed to drive the cane mills, resulting in 3750kW total power. Considering the steam requirement of 35 pounds/kW in these small turbines, about 131,000 pounds of vapor were required to drive the complete cane mill. On the other hand, turbines with high-pressure boilers to drive electrical generators only need 12.7 pound/kW. This means there is a potential of up to 22.3 pounds/kW that can be used to generate electricity instead of being wasted in inefficient turbines driving the cane mills.

Using all of the steam for electric energy generation gives some 10,300kW generating capacity which is used to feed the electrical drives. Furthermore, excess energy of about 6550kW can be sold to the grid. This brings about 1 Million USD/year additional revenue to the Compania Azucarera Hondurena S.A. resulting in a payback time for the MV drive investment of about 1 year!

Besides the remarkable improvement of overall energy efficiency of the plant, there are other clear benefits. The speed of the mill can be accurately controlled depending on the amount of cane coming into the machine. This is a great advantage compared to the use of the steam turbines. Another advantage is that the electrical drives can estimate the shaft torque and protect the mill against overload. In this case the mill can be driven in reverse to get the excess material out of the machine and resume normal operation with minimum production loss.

Further, the ACS 1000 medium-voltage drives require only a fraction of maintenance compared to maintenance intensive steam turbines. This results in a higher up time and lower maintenance costs.

Furthermore, after a shutdown, the cane mill driven by ACS 1000 medium-voltage drives returns to operating conditions much faster than the steam turbine driven cane mill.

Finally, due to ABB's ACS 1000 control method DTC (Direct Torque Control), the noise level is considerably reduced for both the VFD and the motors and is almost negligible compared to that of steam turbines.

V. SELECTION CRITERIA FOR A MV-VFD SYSTEM

A MV-VFD system as discussed in this paper basically consists of an incoming disconnector (fused contactor, main circuit breaker), an isolation transformer with surge protection, the converter (MV-VFD) and its control, MV cables and a MV motor (induction or synchronous). Fig. 6 illustrates a MV-VFD system.

This paper focuses mainly on the converter (MV-VFD) rather than the complementing system components (breakers, transformer and motor), since the VFD is the most complex and probably the least familiar component for most readers.

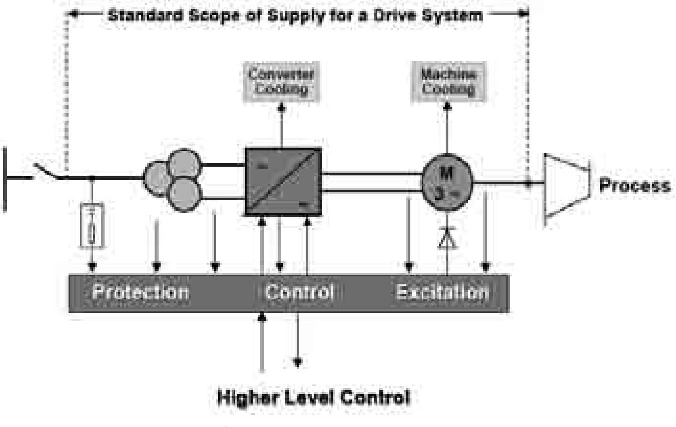


Figure 6. Typical components of a MV-VFD system

A. RELIABILITY

Reliability is probably the most important demand on a MV-VFD. One crucial key to achieve maximum reliability is to design the converter with a minimum of passive and active components. Active components in this context are semiconductor switches (e.g. thyristors, GTOs, IGCTs, IGBTs). Designs with a high parts count, especially active components, cannot, by their physical nature, guarantee the best reliability numbers and should therefore be avoided.

Further, it is recommended that the protection concept is fuseless. Fuses are unreliable and subject to aging. According to [2], more than 7% of all MV-VFD failures are due to blown fuses.

Besides a low parts count, it is also recommended to have reasonable safety margins in the design of all components, which will result in a longer lifetime and consequently in higher reliability.

B. EFFICIENCY

As shown in the previously one of the main benefits of a MV-VFD system is energy savings achieved by running the driven process at its optimum operation point.

In order not to sacrifice this benefit, the MV-VFD itself should also be as efficient as possible. Efficiency numbers of 98.0% or higher are desirable at the nominal operation point. It should be stressed at this point that even small differences of a few points can result in remarkable annual energy costs of several thousand USD.

C. LINE FRIENDLINESS

The number of power electronic circuits connected to the grid is steadily increasing. Each MV-VFD is such a circuit. Due to their non-linear nature, these circuits have the inherent attribute of generating harmonics which have to be limited in order not to cause undesired interactions with other electrical and electronic loads connected to the same bus.

For that purpose, there are standards recommending strict harmonic limits. Examples of these standards are IEEE 519-1992, IEC 61000-2-4 or G5/4 [3]-[5].

In many cases, a 12-pulse input diode rectifier design will fulfill the above-mentioned harmonic standards. In some cases, where the network is weak, an 18-or 24-pulse configuration may be required. This has to be evaluated on a case-by-case basis.

It is, however, questionable to extensively exceed the harmonic standards by means of overly complex transformer configurations and a high parts count, since this contradicts the reliability requirement. In the context of line friendliness, common mode components (i.e. harmonic orders being an odd multiple of three: 3, 9, 15…) should also be considered.

Having an isolation transformer between the MVVFD and the supplying network can mitigate these common mode components. In case of a transformerless MV-VFD system solution, these common mode voltages will be injected into the supplying network.

D. MOTOR FRIENDLINESS

Motor friendliness is another demand on a MV-VFD. This basically means that the driven motor can be a standard DOL (Direct-On-Line) motor, with no special insulation or de-rating needed. This requirement is especially crucial in the case of retrofit applications where an existing (fixed speed) standard motor is upgraded with a MV-VFD.

Ideally, the VFD output voltage should therefore be as close to sinusoidal as possible. In particular, the VFD output voltages at the motor terminals should not exceed the peak-value of the nominal motor voltages and the max. dv/dt should be limited to values of about 500V/us. Further, the current harmonics, being a result of the non-ideal sinusoidal VFD output voltage, should not exceed 5%. The common mode voltages should be fairly low, or even better, nonexistent in order to utilize a standard motor design.

E. CONTROL PERFORMANCE

Another selection criterion for a MV-VFD is its control performance, i.e. its capabilities to accurately control speed and torque and to respond to transient events like load changes in a fast and stable manner. Speed and torque accuracy should be in the range of 0.1%. The required dynamic performance in case of load steps varies with the load. While fan, pumps and compressors require less demanding torque step response times >10ms, applications such as rolling mills may require step response times <5 ms.

Even if high dynamic control performance, i.e. torque response times in the range of 5ms, may not always be required from a process point of view, it is crucial in case of line supply disturbances in order to minimize the impact of such a disturbance on the motor side and the load. The more dynamic a motor control scheme is, the faster it can counteract to these line supply disturbances and the less the impact will be for the mechanical driven load. Further, encoderless motor control schemes are recommended, since encoders are unreliable and may have undesired impacts on the speed control performance.

F. LOW MAINTENANCE

Low maintenance of a MV-VFD is crucial in order to obtain high availability and to keep the life-cycle costs down.

Therefore an ideal MV-VFD is not only reliable but also consists of components which have a long lifetime and do not require regular time- and cost-intensive maintenance. Critical components which should be carefully selected in a MV-VFD design phase, are cooling fans or pumps, cooling system materials (e.g. stainless steel) and DC-link capacitors, which ideally should not be of the electrolytic type (lifetime only about 5 years). Electrolytic capacitors on Printed Circuit Boards (PCB) should be of extended lifetime type and not be operated above 75% of their maximum temperature.

G. FLEXIBILITY

In order to save building costs and costs for indoor HVAC installations, it is a wise idea that the MVVFD and the supplying transformer can be located separately and are not necessarily integrated in the same cubicle. This provides the flexibility to choose between a dry type or oil-immersed transformer located either indoors or outdoors.

In many applications, the actual building size can be smaller (and therefore cheaper) if the transformer is located outdoors. Furthermore, the transformer losses do not have to be handled by an additional HVAC system, which saves extra costs.

Solutions where the MV-VFD supply transformer can be eliminated or replaced by line inductors will certainly result in a smaller footprint, less weight and overall cost savings, but it has to be kept in mind that special design in order to cope with common mode voltages. In addition common mode components will be injected into the line supply system and no galvanic isolation between the feeding supply system and the MV-VFD will exist.

VI. EXAMPLE OF A STATE-OF-THE-ART MVVFD

This section describes ABB's ACS 1000 MV-VFD as an example of a state-of-the-art MV-VFD system, which complies with the basic selection criteria outlined in the previous chapter.

A. GENERAL ACS 1000 INFORMATION

The ACS 1000, launched in 1998, is available for the motor voltages 2.3kV, 3.3kV and 4kV in a power range between 300kW up to 5000kW.

Up to about 1800kW output power, the ACS 1000 product is available with air-cooling, between 1800kW and 5000kW with water-cooling. For photos of the ACS 1000 line-up and the topology, see Fig. 7-8. For further publications on the ACS 1000 VFD, the reader is referred to [7] – [9].

B. IGCT TECHNOLOGY

The chosen semiconductor technology has a major influence on the fulfillment of the previously described MV-VFD selection criteria. The ACS 1000 VFD is based on the IGCT (Integrated Gate Commutated Thyristor) technology, which combines the benefits of the Gate Turn Off Thyristor (GTO) (reliability & robustness, high current density, low on-state losses) and the Insulated Gate Bipolar Transistor (IGBT) (low switching losses, fast switching, snubberless), but eliminates their individual drawbacks. The IGCT is the semiconductor of choice for all MV high power applications and is superior to other semiconductor switches (e.g. IGBT, IEGT, GTO) in regard to reliability, robustness, current density and overall losses (see Fig. 9).

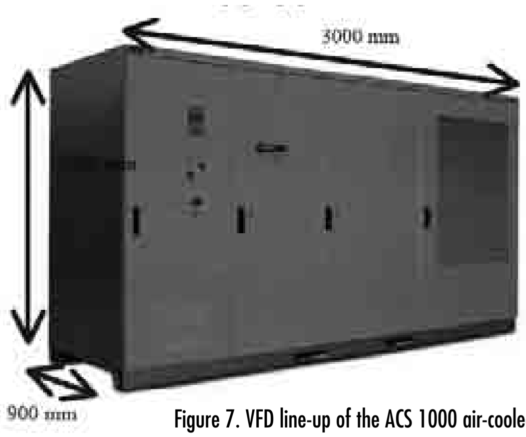


Figure 7. VFD line-up of the ACS 1000 air-cooled version

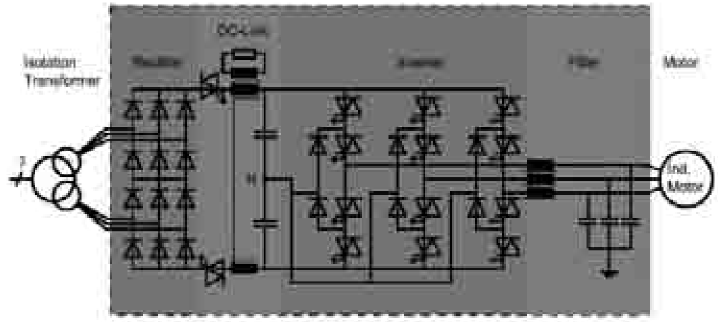


Figure 8. Topology of ABB's ACS 1000 MV-VFD

Figure 9. IGCT module with integrated reverse conducting diode and Gate Unit for ACS 1000

C. RELIABILITY

The IGCT technology enables a compact inverter design that is based on the lowest possible parts count with no series or parallel connection of semiconductor switches.

The inverter unit of the ACS 1000 VFD is a 3-level Voltage Source Inverter (VSI) with just 12 IGCTs with integrated reverse conducting diodes plus some 6 Neutral Point Clamped (NPC) diodes.

The DC link consists of a minimum number of selhealing, high power, film type MV capacitors, which do not need any maintenance.

The standard rectifier, which rectifies the incoming supply voltages from AC to DC, is a simple 12-pulse diode bridge with high power MV diodes, resulting in the minimum parts count of not more than 12 diodes. Further, the protection concept is not based on fuses but on 2 additional IGCTs, the so-called protection IGCTs, which are located between the 12-pulse diode rectifier and the DC-link capacitors, see Fig. 8. The protection IGCTs are not only much more reliable than fuses, they are also about 100 times faster (about 25μs) and do not have to be replaced after the rare event of a failure. Moreover, the ACS 1000 components are designed with safety margins, which results in an overall Mean Time Between Failure (MTBF) number of 51,000 hours or 5.8 years. Finally, the design of the ACS 1000 VFD is very service friendly. In case of a failure, it can be repaired in a minimum time (e.g. exchange of a diode or IGCT takes only 15-30 min.), which shows its impact in a high availability number of 99.93%.

D. EFFICIENCY

Due to the minimum number of semiconductor components and the very efficient IGCT technology, the efficiency of the ACS 1000 VFD is excellent. This is based on the fact that IGCTs show the overall lowest losses compared to other semiconductor switches like

GTOs or IGBTs. Even if the output sine filter contributes with some points to the loss balance, the overall ACS 1000 VFD efficiency (incl. aux. losses) at the nominal operation point is typically around 98.5%.

E. LINE FRIENDLINESS

The standard 12-pulse diode rectifier bridge fulfills the strict harmonic standards for most applications. To quantify this statement, see Fig. 10, which shows the network voltage and currents generated by an ACS 1000 12-pulse diode bridge and benchmarked against

IEEE519 for a typical industrial network. It can be clearly seen that the IEEE519 standard is not only fulfilled but even exceeded. In cases where the network is very weak, a 24-pulse option is available. Also the supply side power factor is only varying slightly over the whole load range and is typically better than 0.95.

F. MOTOR FRIENDLINESS

The ACS 1000 VFD features almost pure sinusoidal output voltages and currents and is therefore perfectly suited to drive standard motors with no special insulation or de-rating requirements. Even very old motors can be retrofitted with the ACS 1000. For output voltage and current waveforms, please refer to Fig.11.

In addition, the unpopular common mode voltages are eliminated at the motor terminals, since they are exclusively captured inside the ACS 1000 VFD.

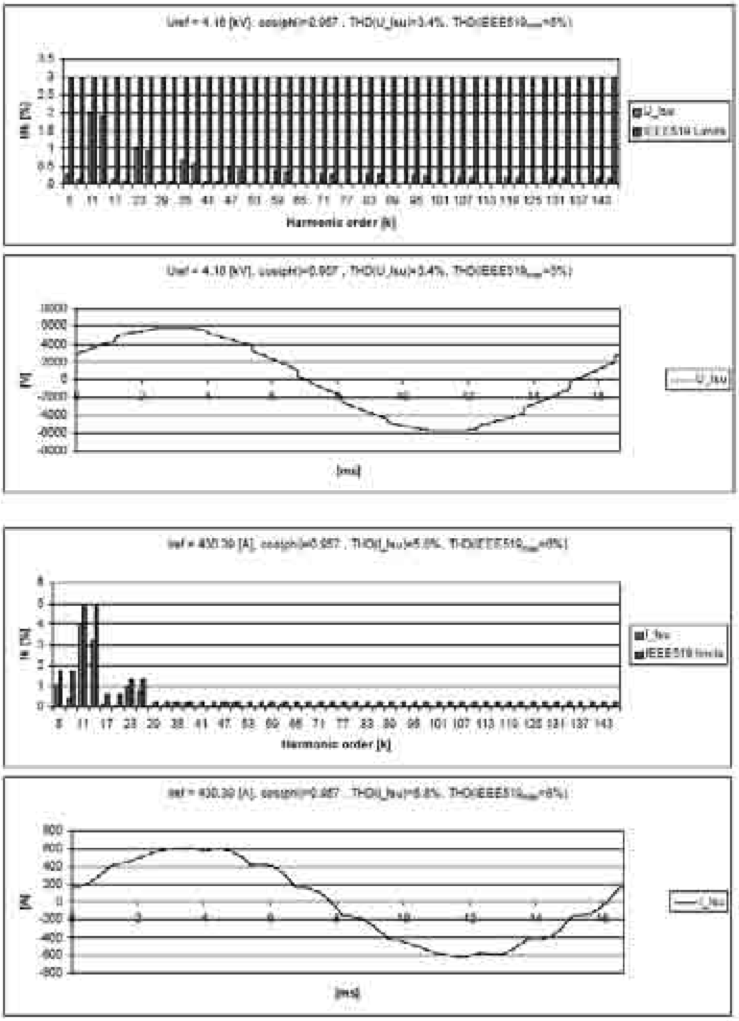


Figure 10. Harmonic spectrum benchmarked against IEEE519 limits and line diagram of the voltage and current generated by an ACS 1000 VFD with 12-pulse diode rectifier input, $I_{SC}/I_L=25$, I_{SC}=network short circuit current, I_L=nominal ACS 1000 drive current

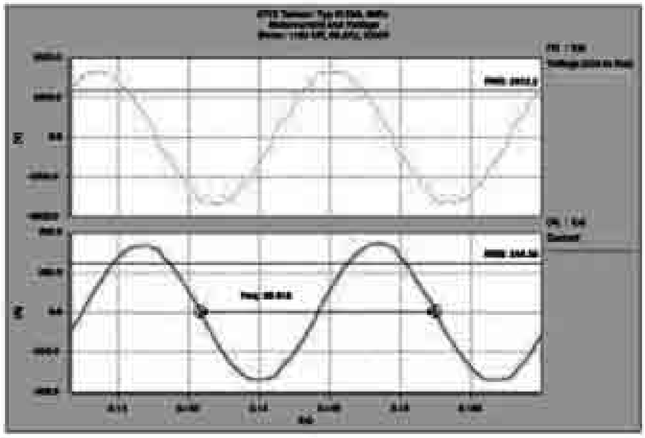


Figure 11. Filtered line-line ACS 1000 output voltage (upper trace) and corresponding motor currents (lower trace)

These ideal output voltages are achieved with the integrated sine filter, see Fig. 12. Further, since the sine filter star-point is grounded, it is guaranteed that the driven motors are not opposed to common mode voltages. Another remarkable benefit is an almost unlimited cable length between the VFD output and the motor (no voltage reflections at the end of the cable).

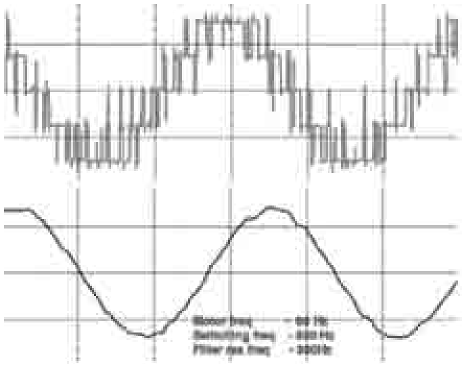


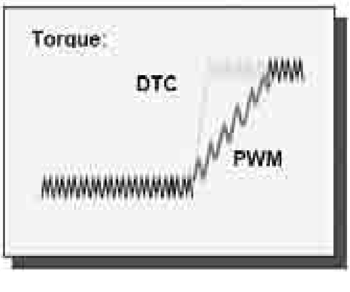
Figure 12. Unfiltered (upper trace) and filtered (lower trace) line-line ACS 1000 output voltage

G. CONTROL PERFORMANCE

The control method of choice in ABB's ACS 1000 product is the so-called Direct Torque Control (DTC). This, ABB-patented, control scheme is undeniably the most dynamic and efficient control scheme existing on the drives market today.

With DTC, both the torque and the flux of the motor are kept within a given hysteresis band, which is checked every 25µs. Switching of the semiconductors does not occur according to a fixed determined pulse pattern, but only if one of the two controlled quantities touch the hysteresis band limits. In this case however, the switching will be immediate. This algorithm ensures an unmatched static (speed accuracy < 0.1%) and dynamic control with no overshoot during transient torque steps and step response times as low as 1-2ms (see Fig. 13). Additionally, the switching frequency, and with that the switching losses, will be kept at a minimum. Another positive side effect is a very low motor noise. This is due to the fact that the harmonic spectrum of the motor voltages is distributed over the whole frequency range with low amplitudes rather than having distinctive harmonic orders with high amplitudes.

Figure 13. Torque step-response of DTC compared to conventional PWM control scheme



H. LOW MAINTENANCE

The required maintenance is more or less limited to exchanging (intervals depending on the ambient conditions) a few items such as the air filter in the case of an air-cooled drive (once a year) or the deionizer vessel in the case of a water-cooled version (every second year) or the back-up battery (every second year). In addition to the basic maintenance, ABB offers maintenance contracts, which include additional checks (not replacements!), which, in the course of time, will result in higher reliability and availability at a minimum cost.

I. FLEXIBILITY

The ACS 1000 product provides the flexibility to have the VFD isolation transformer located indoors in the line-up of the drive or outdoors, separated from the drive. Either a dry-type or an oil-immersed transformer can be chosen. Should the preference be to have the isolation transformer in the line-up of the drive, a repackaged aircooled ACS 1000, namely the ACS 1000i, is a very interesting alternative (Fig. 14). It is a highly compact drive (L x D x H = 3.3m x 1.1m x 2.7m) with incoming breaker, isolator switch, surge protection, 24-pulse transformer and the VFD integrated in one cubicle (= 3 cables in, 3 cables out).

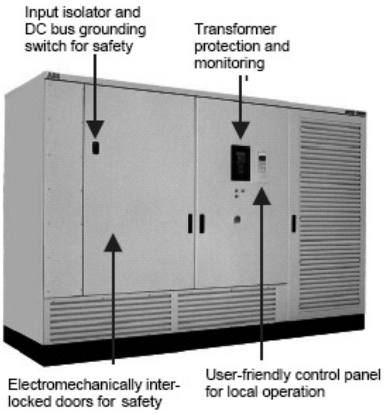

Input isolator and DC bus grounding switch for safety
Transformer protection and monitoring
Electromechanically interlocked doors for safety
User-friendly control panel for local operation

Figure 14. ABB's ACS 1000i VFD with integrated switchgear, protection and 24-pulse VFD isolation transformer

VII. CONCLUSIONS

The multiple benefits of a MV-VFD system were introduced in this paper. It was shown that, in the sugar industry as well as in many other industries, various applications can benefit from the application of a MV-VFD system. This was highlighted by two examples:

a) the most innovative mechanical vapor compressor application at Al Khaleej Sugar, where ABB's ACS 1000 drive family is applied as a soft-starting device
b) the replacement of inefficient steam turbines for a cane mill application at Compania Azucarera Hondurena S.A.

Following this, basic selection criteria for a MV-VFD were given and finally, ABB's ACS 1000 drive family, as an example of a state-of-the-art MV-VFD, was presented.

VIII. REFERENCES

[1] H. Krattiger, C. Bondoni, H. Kobi, H. D. Remorini, "Increase Competitive Level by replacing Steam turbines with Electric Adjustable Speed Drive System", IEEE PCIC 2004 conference in San Francisco.

[2] Robert A. Hanna and Shiva Prabhu, "Medium-Voltage Adjustable Speed-Drives – Users' and Manufacturers' Experiences", IEEE Transactions on Industry Applications, Vol. 33, No. 6, Nov/Dec 1997

[3] "IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems", IEEE standard 519-1992

[4] "Electromagnetic Compatibility (EMC) – Part 2-4: Environment – Compatibility levels in industrial plants for low frequency conducted disturbances", IEC 61000-2-4 International Standard, Second Edition 2002-06

[5] "Planning levels for harmonic voltage distortion and the connection of non-linear loads to transmission systems and public electricity supply systems in the United Kingdom", Engineering recommendation G5/4

[6] Virgil Dudgeon, Bob Grasse, L.C. Krishnan, "Energy cost reduction by using Mechanical Vapour Recompressors", Sugar Industry Technologists 2005 Annual Technical Conference, April 3-6, 2005, Dubai, UAE.

[7] A. Sapin, P. K. Steimer, J. J. Simond, "Modelling, Simulation and Test of a Three level Voltage Source Inverter with Output LC Filter and Direct Torque Control", 2003 IEEE Industry Applications Conference, 38th Annual Meeting, Oct. 12-16, Salt Lake City, USA

[8] J. K. Steinke, R. Vuolle, H. Prenner, J. Jarvinen, "New Variable Speed Drive with proven motor friendly performance for medium voltage motors", Proceedings of the International Electric Machines and Drives Conference (IEEE-IEMDC '99), May 9-12, 1999, Seattle, USA

[9] P. Pohjalainen, P. Tiitinen, J. Lalu, "The next generation Motor Control method – Direct Torque Control (DTC)", Proceedings of the EPE Chapter Symposium on Electrical Drive Design and Application, 1994, Lausanne, Switzerland.

MAKING THE CHOICE BETWEEN LOW-VOLTAGE AND MEDIUM VOLTAGE DRIVES

High power applications now have motor control solution options – either low-voltage or medium-voltage drives. Find out how to analyze your options and determine the best solution for your specific application…

Historically, the task for low voltage users has been relatively straightforward; choose one supplier from many in the market, based on a number of criteria including price, reliability, functionality, and communications. However, for a drive control solution for larger industrial loads, the situation is not so clear-cut. Until quite recently, most engineers faced with a high power application would choose a low-voltage (LV) drive system working at very high levels of current. The alternative of a medium-voltage (MV) drive was not very attractive, due to perceived high purchase cost, physical size, requirement for custom engineering and high installation costs. Recently though, the MV drive has shed this costly and unwieldy image and is offering a real alternative to LV drives in the higher power sector; especially where installations are judged across a wide range of criteria, rather than just initial drive cost.

THE NEW MEDIUM VOLTAGE DRIVES

There are a number of reasons for heightened levels of interest in MV drives: increased selection – most major manufacturers now have an MV product; advances in power semiconductor switches – new devices such as SGCTs (symmetrical gate-commutated thyristors) improve packaging, increase reliability, and reduce overall drive cost; and standardisation – in the past most, MV drives were highly engineered products with lead times of six months or more. Today, greater levels of standardisation are substantially reducing delivery times for most ‘standard’ MV drives.

DRIVE COMPARISON ANALYSIS

The emergence of MV drives and their greater acceptance, generally, should not imply that the solution to every high-power application is an MV drive. No two applications are the same, and this means that, in applications where there is more than one possible solution, (i.e. LV or MV), then the most cost-effective strategy is to conduct an analysis of the benefits of the two potential systems.

POWER

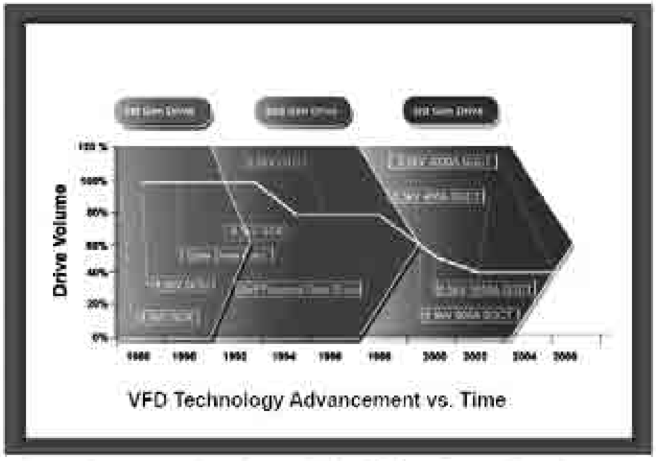
In some cases comparisons are unnecessary as the decision to go LV or MV is simply a question of the amount of power available in the distribution network at each voltage. If adequate power is available at more than one voltage rating, then the choice of selecting LV or MV has to be based on another factor.

COST

The first area to be considered is cost. Even with recent developments, medium-voltage AC Drives are not inexpensive; typically, the cost of a low-voltage AC Drive and an Output (Step-Up) Isolation Transformer is only 50% to 75% of the initial cost of a medium voltage AC drive. However, as the application current increases, the system fault current also increases. This may have safety repercussions and could affect the cost of the drive system. However, initial price is only part of the total solution, and, as we shall discuss later, when the costs for cabling and installation are added, the equation between the two drive options may be balanced out.

DRIVE TOPOLOGY

After initial cost considerations, the question becomes one of technical issues, such as: what drive architecture, or topology, is best suited to provide continuous, efficient and reliable operation at high power? This question is fundamental, because, at high power, the equipment investment is greater, as are the demands of the application. This means that VFD output power quality is an extremely important consideration for protecting the motor investment and ensuring its continued availability. In terms of LV architectures, the most common is PWM (Pulse Width Modulation) VSI technology. This offers good levels of reliability, but does suffer losses in efficiency with each on/off switching transition. In addition, the true levels of voltage and dv/dt rise produced by the pulse width modulation of voltage operation may cause reflected waves, motor insulation stresses and ground fault currents.



Advances in power semiconductor switches in PowerFlex medium voltage drives have improved packaging, reduced size, increased reliability and reduced overall drive cost.

HARMONICS REDUCTION

As more applications convert to VFD control, there is a greater emphasis by utilities to comply with harmonic standards such as IEEE 519, EN61000-2-4 and G5/4. Therefore, VFD manufacturers have incorporated methods to reduce harmonics in their VFD designs. With high-pulse number LV VFDs, and some MV drives, one common method of achieving harmonic reduction is through an isolation transformer with multiple phase-shifted secondary windings. These work on the principle of "the higher the pulse number, the greater the degree of harmonic reduction".

However, at high pulse numbers, of 24-pulse and greater, it is difficult to balance the electrical symmetry of the transformer secondary windings. In addition, some manufacturers have limitations on the distance between the VFD and transformer to prevent overheating problems.

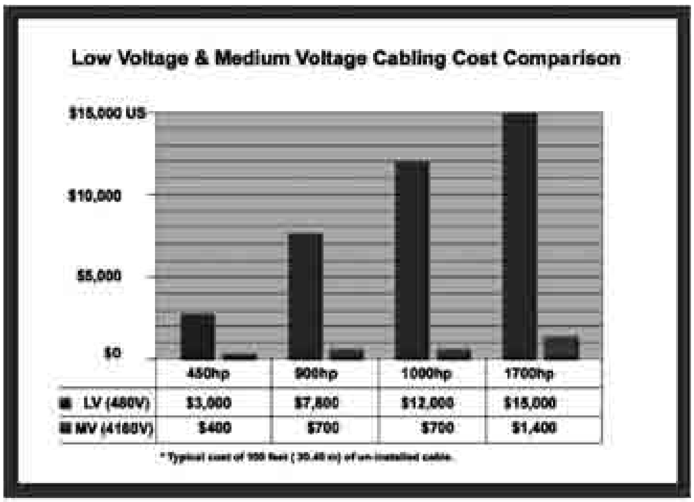
REDUCED SIZE AND WEIGHT

The ability of Direct-to-Drive technology to save space also impacts two other areas where a direct comparison between LV and MV drives is essential: their relative size and weight. When analyzing these factors it is important to include all components that make up the drive solution: the VFD; the input impedance; output impedance; input disconnect device; and input and output filters. This is not a problem with MV systems as they are traditionally supplied as totally integrated and cabled solutions.

Manufacturers often provide the system components separately because of a number of advantages: the ability to distribute components of the system throughout areas such as control rooms; easier movement of components through areas of restricted space during installation; components being lighter to move individually; and, finally, cooling of the drive. In general terms, though, a packaged LV system would definitely be smaller and lighter than an MV system based upon conventional architecture.

CABLING COSTS

Cable cost must be determined as part of the VFD solution because of its impact on total cost of ownership. Cable size and cost vary with the level of current they conduct: the higher the current, the larger the cable and the greater its cost. This means that for LV drives at high power, cable and installation costs are high. In addition, LV installations require expensive shielded EMC (Electro-Mechanical Compatibility) cable. The contrasting expense for MV systems is much less, due largely to the lower current their cables carry, and the fact that they do not need to employ EMC shielded cables. The example below shows that the cable cost difference between the 480V and the 4160V VFD solutions grows disproportionately as the motor current increases. Moreover, the distance between the sources, the VFD and the motor have a big impact on cable cost, especially at high powers.



COOLING COSTS

In addition to cabling, another cost that must be included when comparing VFD solutions is cooling. All equipment that uses or handles power generates a certain amount of heat. With high-power drive systems in enclosures, this heat can be a particular problem. Consider LV drives; most are air cooled, and at high power, heat losses can become significant: for example: a 3% loss at 2MW is 60kW, a figure which would well justify the use of air conditioning to cool the drive and its associated components. The alternative of liquid cooling effectively removes about 90% of the heat generated by the VFD losses out of a control enclosure, but involves additional costs for pumping cabinets and heat exchangers if not already available on site. The decision between air conditioning or liquid cooling is usually application-based, and best made after assessing the availability of either option at the site. For example, in the water industry the availability of liquids and pumping equipment may offer distinct benefits when selecting liquid cooling solutions.

COMMUNICATIONS

An important consideration in the LV versus MV debate is communications. For users, the question is: if I choose an MV drive will it give me the same capability for integration into factory-wide automation networks as LV drives? LV drives are more commonly associated with the communication interfaces that facilitate factory networks.

Finally, there has to be the question of service and maintenance. Many plant maintenance engineers are comfortable with LV AC drive applications, but have concerns regarding medium-voltage applications, which they may see as very complex solutions that are almost always installed, commissioned and maintained by the drive supplier. The concerns are expense and dependence on the manufacturer.

How relevant these concerns are today is debatable: certainly custom engineered products of the past were unwieldy and required highly specialized attention, usually above and beyond that available from internal plant personnel. However, the move to more modular MV systems is simplifying MV structures, making their acceptance more widespread and their application more understood in the same way as LV types. The decision to re-evaluate pre-conceived perceptions when looking at both solutions and taking into account the discussed points may result in a change in solution or may re-affirm your choice in the solution you currently adopt. The informed choice is now yours.

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